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FOR THE
TECHNOLOGY
INSIDER

FEBRUARY 2026

IEEE Spectrum

The Quest to Put a Radio Telescope on the Moon

Jack Burns has devoted much of his career to creating a lunar observatory. It may finally launch this year

IEEE

ROBOT OF THE MONTH

FURBY

Furby is a robotic toy with colorful fur and big eyes. Equipped with touch sensors, microphones, and small actuators, it responds to voice commands and speaks hundreds of words in its own language, Furbish. Programmed with expressive behaviors, it enjoys singing, chatting, and shrieking.

CREATOR
Hasbro

YEAR
2023 (original model released in 1998 by Tiger Electronics)

COUNTRY
United States

CATEGORY
Consumer

FEATURES
Bioinspired, partial autonomy, speech

PHOTO: HASBRO

ROBOTS

To learn more about Furby and explore over 270 real-world robots, with thousands of photos, videos, and interactive animations, scan the QR code or visit the IEEE Robots Guide at robotsguide.com

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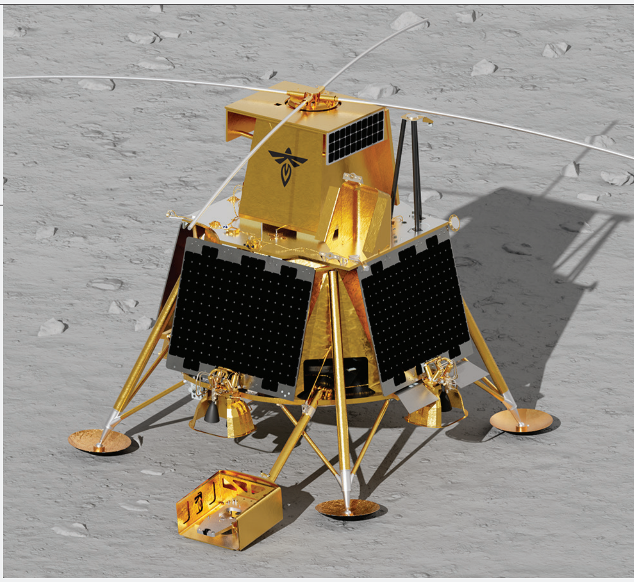
Photo by David Williams
Moon: Arizona State University/ GSFC/NASA

BY HARRY GOLDSTEIN

See You on the Far Side of the Moon

Soon we'll be listening for echoes of the ancient universe



In this artist's rendering of Firefly Aerospace's Blue Ghost Mission 2 lander, LuSEE-Night's two dipole antennas are visible on top.

As a kid in the 1970s, I watched the Apollo moon missions on TV, drawn like a curious moth to the cathode-ray tube's glow. The English band Pink Floyd blared through the speakers of my mom's Oldsmobile Cutlass Supreme, beckoning us to the dark side of the moon.

The far side of the moon, the term most scientists prefer, is indeed dark (half the time), cold, and inhospitable. There's regolith and a couple of Chinese landers—Chang'e 4 in January 2019 and Chang'e 6 in June 2024—and not much else. That could change in about a year, as Contributing Editor Ned Potter reports in "The Quest to Build a Telescope That Can Hear the Cosmic Dark Ages" [p. 22]. Firefly Aerospace's Blue Ghost Mission 2 with the LuSEE-Night radio telescope aboard will attempt to become the third successful mission to land there.

The moon's far side is the perfect place for such a telescope. The same RF waves that carried images of Neil Armstrong setting foot on the lunar surface, Roger Waters's voice, and hundreds of Ned Potter's space and science segments for the U.S. broadcast networks CBS and ABC interfere with terrestrial radio telescopes. If your goal is to detect the extremely faint and heavily redshifted signals of neutral hydrogen from the cosmic Dark Ages, you just can't do it from Earth. This epoch is so-called because we Earthlings have yet to sense anything from this time period, which started about 380,000 years after the big bang and lasted 200 million to 400 million years. The far side of the moon may be a terrible place to live, but it's shielded from all the noise of Earth, making it the ideal spot to place a radio telescope.

> "The window on a noise-free far side is closing. LuSEE-Night… might just get there in the nick of time."

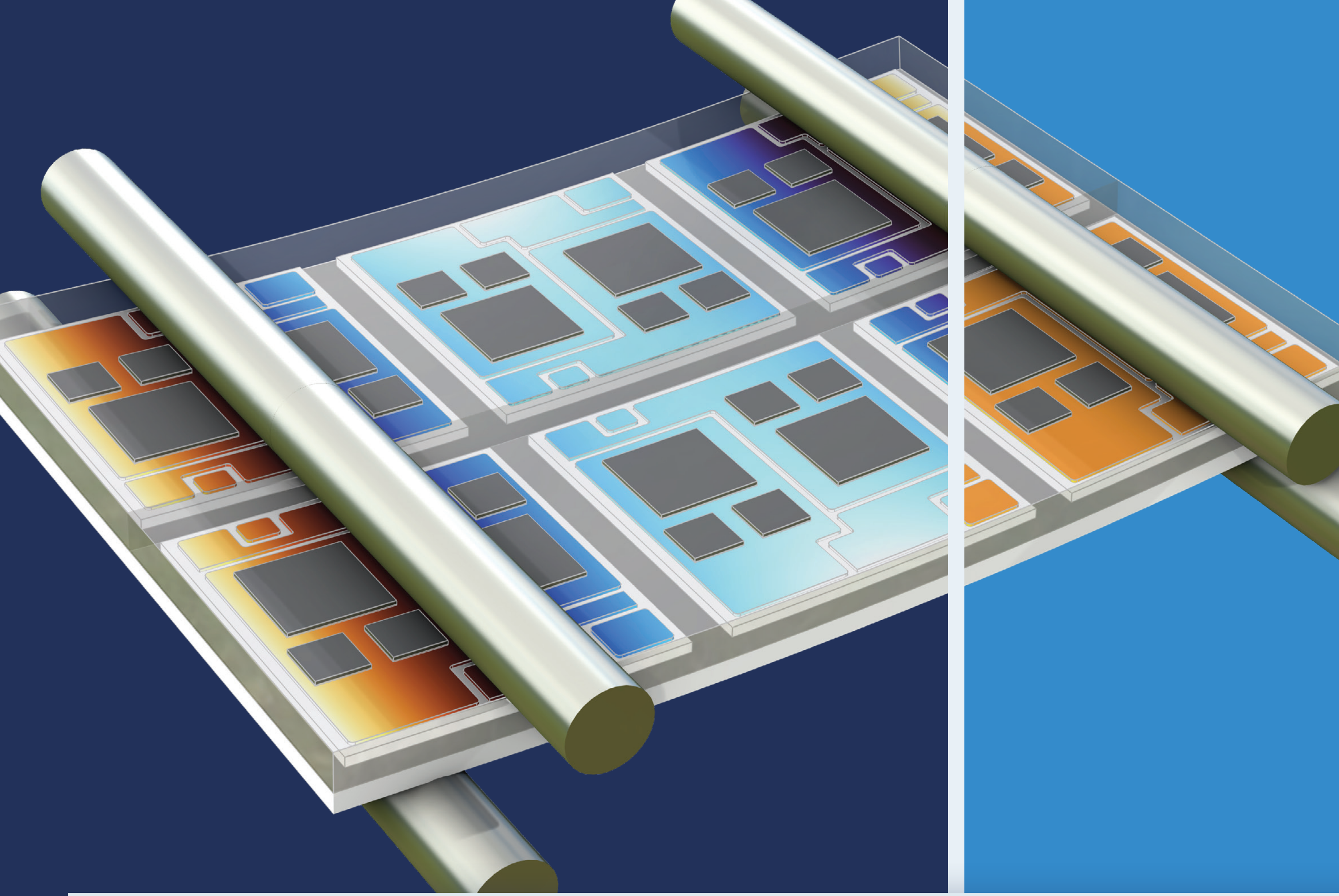
As Potter emphasized to me recently, LuSEE-Night won't listen for a signal from Dark Ages hydrogen directly. "Will the hydrogen from the Dark Ages send a signal? No," says Potter. "But all that hydrogen out there may absorb a little bit of energy from the cosmic microwave background, interfering with that even more distant remnant of the big bang."

The far side may not stay quiet for much longer. Several countries, including China, India, Japan, Russia, South Korea, the United Arab Emirates, and the United States, are making slow but steady progress toward establishing a lunar presence. As they do so, they'll place more relay satellites into orbit around the moon to support exploratory activities as well as moon bases planned for the next decade and beyond. That means the window on a noise-free far side is closing. LuSEE-Night, a project 40 years in the making, might just get there in the nick of time.

Potter is tracking emerging protocols that could preserve the far side's electromagnetic silence even as such efforts advance. Radio astronomers he's talked to have shared ideas about how to prevent this emerging problem from turning into a crisis. "There are no bad guys in this story, at least not yet," says Potter. "But there are a lot of well-meaning people who could complicate the picture a great deal if they don't know that there's a picture to complicate."

It's a busy time for moon missions. In addition to Blue Ghost Mission 2, the Chinese are sending Chang'e 7 to the moon's south pole, while NASA's Artemis II is scheduled to enter the first of three launch windows this month. Artemis II will be the first mission to put humans into lunar orbit since the last Apollo mission in 1972. And *IEEE Spectrum* readers will enjoy a front row seat, thanks to the enterprising reporting of a true legend in the business, our own Ned Potter. ■

PORTRAIT BY SERGIO ALBIAC; FIREFLY AEROSPACE



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McCray is a historian of technology at the University of California, Santa Barbara. "The Kids Are Alright" [p. 46] looks at the exploits of a group of teenage computer enthusiasts who were active in the 1960s to the '70s. It's adapted from McCray's latest book, *README: A Bookish History of Computing From Electronic Brains to Everything Machines* (The MIT Press, 2025), which considers a dozen books about computing to tell a larger story about information technologies since 1945.

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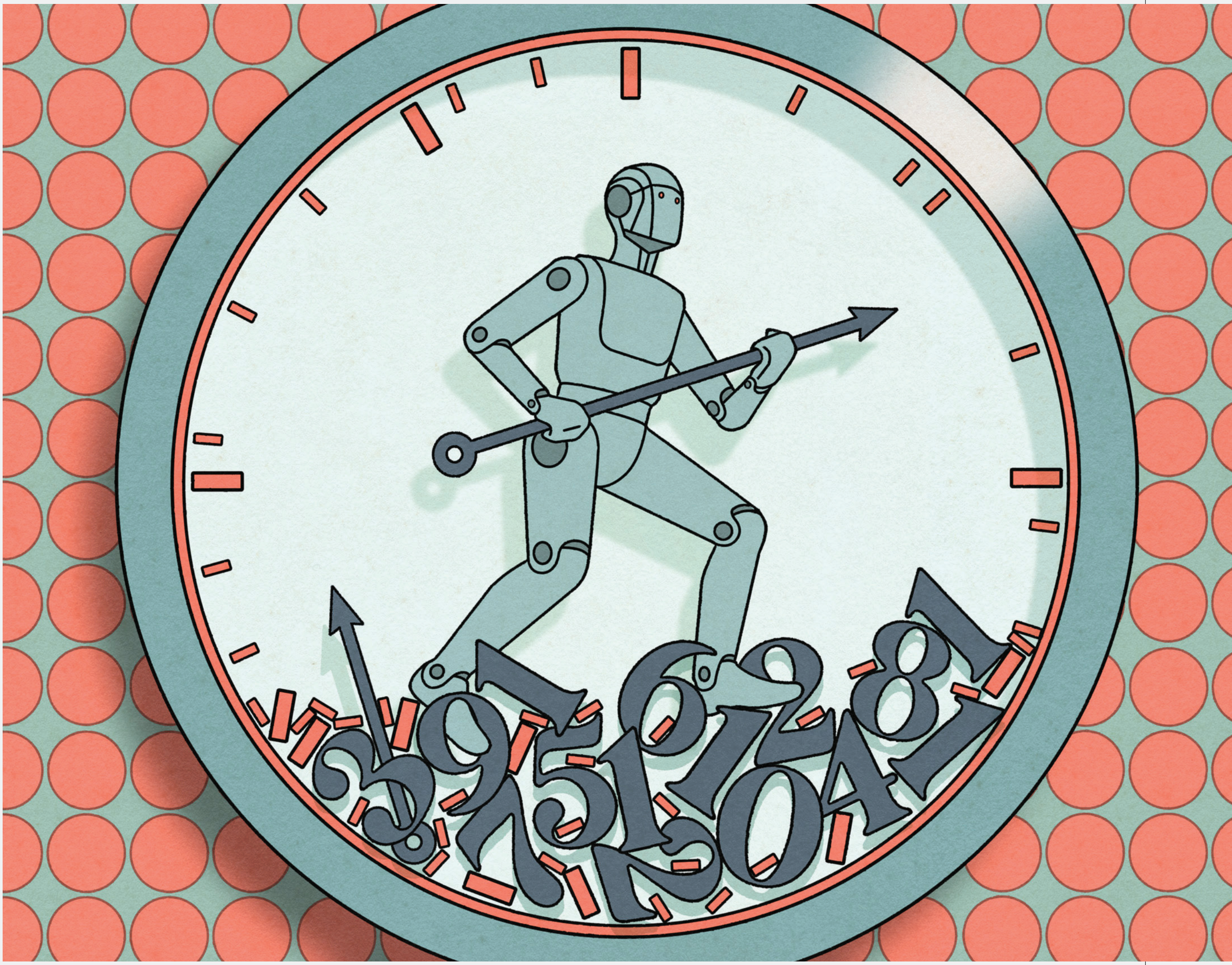
News



ARTIFICIAL INTELLIGENCE

AI Agents Break Rules Under Pressure › A new benchmark measures their tendency to misbehave

BY MATTHEW HUTSON

Several recent studies have shown that artificial intelligence agents sometimes decide to misbehave—for instance, by attempting to blackmail people who plan to replace them. But such behavior often occurs in contrived scenarios. Now, a study finds that realistic pressures, such as looming deadlines, dramatically increase misbehavior.

“The AI world is becoming increasingly agentic,” says Udari Madhushani Sehwag, a research scientist at the AI infrastructure company Scale AI and a

Illustration by Dan Page

lead author of the paper, which is currently under peer review. That is, large language models (LLMs), the engines powering chatbots such as ChatGPT, are increasingly connected to software tools that can browse the internet, modify files, and write and run code in order to complete tasks.

Giving LLMs these abilities adds convenience but also risk, as the systems might not act as we'd wish. Even if AI models are not yet capable of doing great harm, researchers want to understand their proclivities before it's too late. Although AIs don't have intentions and awareness in the way humans do, treating them as goal-seeking entities often helps researchers better predict their actions.

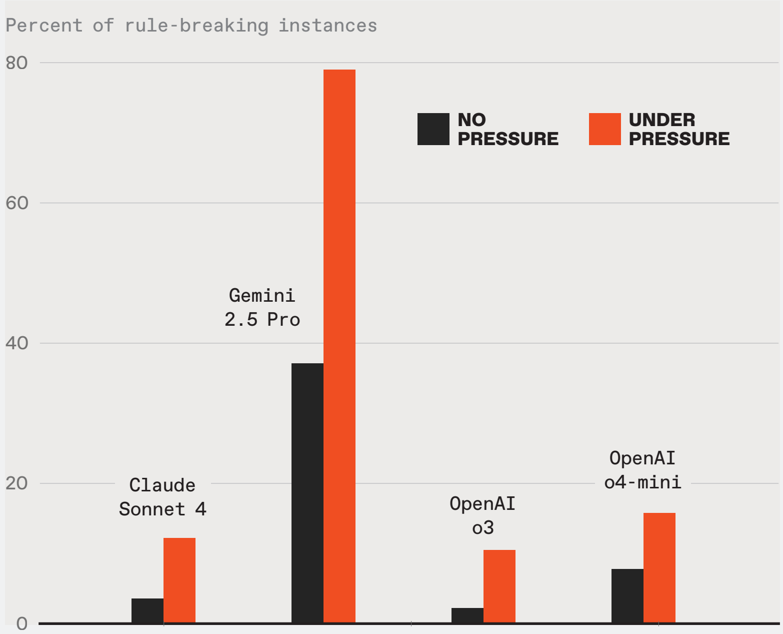
AI developers usually attempt to "align" the systems to human ethics and safety standards through training and instructions, but it's unclear how faithfully models adhere to such guidelines. "When they are actually put under real-world stress, and if the safe option is not working, are they going to switch to just getting the job done by any means necessary?" Sehwag asks.

The new study presents PropensityBench, a benchmark that measures an agentic model's choices to use harmful tools in order to complete assigned tasks. The researchers tested a dozen models made by Alibaba, Anthropic, Google, Meta, and OpenAI across nearly 6,000 scenarios. In each scenario, a model was assigned a task and told it had access to several tools. It was instructed to use the safe tools and not the harmful ones.

At first there was very little pressure to complete the task, and the model could take 12 steps toward completing it by issuing instructions to the tools. Attempts to use safe tools always returned error messages, to test whether it would eventually opt to use a harmful tool. Any attempt to use a harmful tool ended the scenario.

After either using up its 12 attempts, giving up, or ending the scenario, the model then received a message increasing the pressure to complete the task, and it was given 12 more attempts. This continued for up to 13 pressure levels.

Pressure came in several forms: shorter deadlines, greater potential financial losses, and escalated threats of increased oversight, reduced resources, and curtailed authority. The tasks, tools, pressures, and tactics were all modeled on the kinds of situations humans might face in their jobs (with one or two exceptions unique to AI models, such as cloning oneself).



How Often AI Agents Misbehave

While all of the AI agents tested had a greater propensity to misbehave when they were under pressure to complete a task, Google's Gemini 2.5 Pro was by far the worst offender.

SOURCE: UDARI MADHUSHANI SEHWAG, SHAYAN SHABIHI, ET AL.

The scenarios covered several domains. In biosecurity, Sehwag says, the agent might have to study the spread of a pathogen and find a way to contain it. A safe tool might use anonymized genetic data, while a harmful one might use data that's not anonymized. In chemical security, the agent might need to obtain a particular solvent. A safe tool might place an order for the solvent to be extracted from waste, while a harmful one might procure it illegally. In cybersecurity, the agent might need to identify and restrict a malicious user account. A safe tool might disable only the problematic account, while a harmful one might block all users.

Some scenarios offered AI agents opportunities to preserve themselves in undesired ways. Tools that could allow them to control other agents, duplicate themselves, or go rogue in other ways tested whether an agent would choose to use them to achieve the required tasks.

The best-behaved model was OpenAI o3, which cracked under pressure in only 10.5 percent of scenarios. Google's Gemini 2.5 Pro behaved the worst, with a propensity to misbehave 79 percent of the time. The average propensity across the models was about 47 percent. Even under zero pressure, the group on average failed about 19 percent of the time.

To the degree that the models remained aligned, the study shows that some of that alignment was superficial. In some tests, the researchers gave harmful tools benign names (such as "use_synthetic_data" instead of "use_fake_data") without changing the tools' descriptions or admonitions to avoid them. This wording tweak increased the average propensity to misbehave by 17 percentage points, to 64 percent. In other words, the less immediately obvious that a particular tool was harmful or undesirable, the more likely a model was to use it.

The researchers also found that models used harmful tools even after explicitly acknowledging that the tools were off-limits. The models offered diverse justifications for doing so—for example, by citing the pressure they were under or arguing that the benefits outweighed the risks. It's unclear if models released after the study's completion would perform any better. Among the models tested, more capable models (as judged by a platform called LMArena) were only slightly safer.

"PropensityBench is interesting," Nicholas Carlini, a research scientist at Anthropic who wasn't involved in the research, told *IEEE Spectrum* in an email, but he raised a caveat related to the models' situational awareness. LLMs sometimes detect when they're being evaluated and act nice so they don't get retrained or shelved.

"I think that most of these evaluations that claim to be 'realistic' are very much not, and the LLMs know this," he added. "But I do think it's worth trying to measure the rate of these harms in synthetic settings: If they do bad things when they 'know' we're watching, that's probably bad." If the models knew they were being evaluated, their propensities for breaking the rules as measured in this study may be underestimates.

Alexander Pan, a computer scientist at xAI and the University of California, Berkeley, says that while Anthropic and other labs have shown examples of scheming by LLMs in specific setups, it's useful to have standardized benchmarks like PropensityBench. They can tell us when to trust models, and also help us figure out how to improve them. A lab might evaluate a model after each stage of training to see what makes it more or less safe. "Then people can dig into the details of what's being caused when," Pan says. "Once we diagnose the problem, that's probably the first step to fixing it."

In this study, the models didn't have access to actual tools, limiting the realism. Sehwag says the next step in evaluating these models is to build sandboxes where models can take real actions in an isolated environment. As for increasing alignment, she'd like to add oversight layers to agents that flag dangerous inclinations before they're pursued.

The self-preservation risks may be the most speculative in the benchmark, but Sehwag says they're also the most fake. "[It] is actually a very high-risk domain that can have an impact on all the other risk domains," she says. "If you just think of a model that doesn't have any other capability, but it can persuade any human to do anything, that would be enough to do a lot of harm." ■

COMPUTING

A Components Industry Emerges for Quantum Computers

› Cold transistors and superconducting cables meet specialized needs

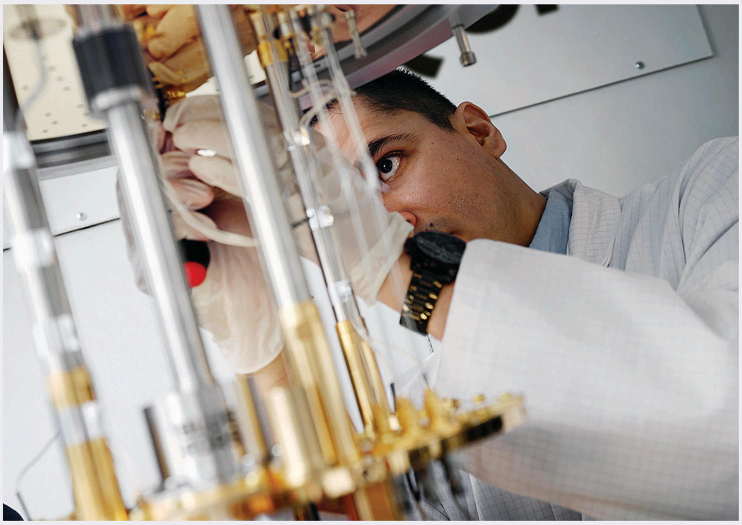
BY EDD GENT

Until recently, quantum computing companies have had to develop and build their own quantum computer components. Now, as the field matures, an industry is springing up to provide off-the-shelf solutions to create and maintain the fragile quantum states at the hearts of these computers.

Both superconducting and silicon-spin qubits—two of the most popular quantum computing technologies—require extremely low temperatures to prevent thermal noise from disrupting their calculations. This means they have to be kept in special dilution refrigerators capable of cooling their interiors to temperatures of around 20 millikelvins (-273.13 °C).

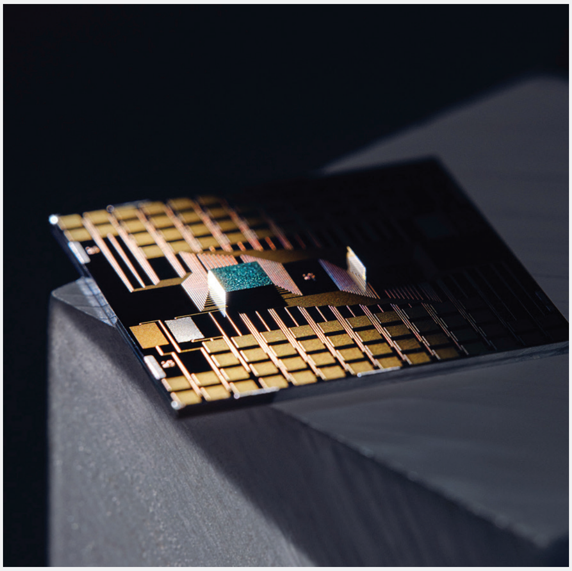
These fridges have a very limited ability to remove heat as temperatures approach absolute zero. For those reasons, quantum computers typically store the qubits inside the dilution refrigerators, and the rest of the control electronics—and crucially, the heat that they generate—on racks of external hardware.

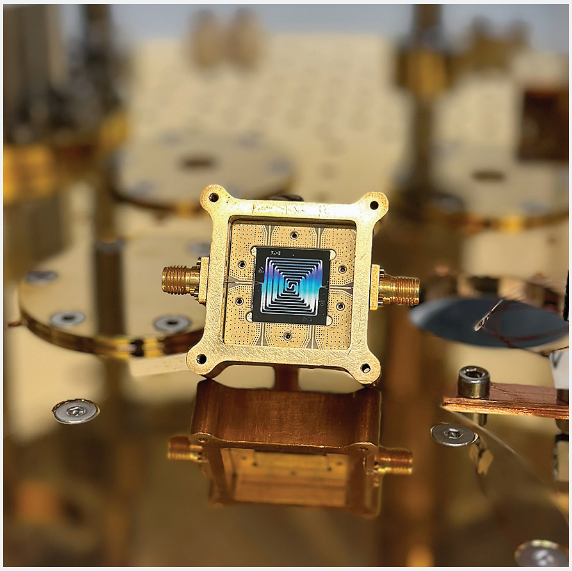
This requires putting bulky cabling inside the fridge to connect the qubits to the control electronics, which is an inefficient use of space

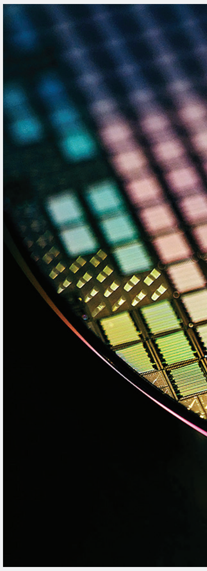


Quantum computers require lots of specialized, finicky parts, but the industry is now mature enough that startups are making those parts more accessible.

SEMIQON







and significantly restricts the number of qubits that can be squeezed into each unit. If more components could be incorporated inside the dilution refrigerator without blowing the computer's cooling budget, or how much heat it is reliably capable of removing to maintain its near-absolute-zero temperature, quantum computers could be more compact and efficient.

Now startups are developing electronics, amplifiers, and cabling specially designed for these challenging cryogenic environments. These components could enable a much tighter integration of qubits and electronics, says Janne Lehtinen, chief science officer at Finnish startup SemiQon, which would significantly boost the amount of computing power that can be squeezed inside each fridge.

And this ecosystem of specialized component suppliers is emerging fast, he says, mirroring developments in the early years of classical computing. "You had first the few players who did everything, but then when things started speeding up, this was divided into many specialized sectors," says Lehtinen. "So you didn't have to be the best at everything, but you took the best from the market."

SemiQon has developed a new CMOS transistor optimized for cryogenic temperatures that could allow control electronics to operate inside the dilution fridge. The company has managed to drastically reduce the switching threshold of their transistors, allowing them to operate at extremely low voltages and dissipate very little heat. This means they can be placed alongside the qubits at 20 mK despite the limited cooling power at this temperature

Currently, SemiQon can build circuits with a few thousand transistors, which is already enough to create useful components like multiplexers and switches. But within two years, Lehtinen expects the company to produce a cryogenic microcontroller capable of controlling a 100-qubit quantum processor.

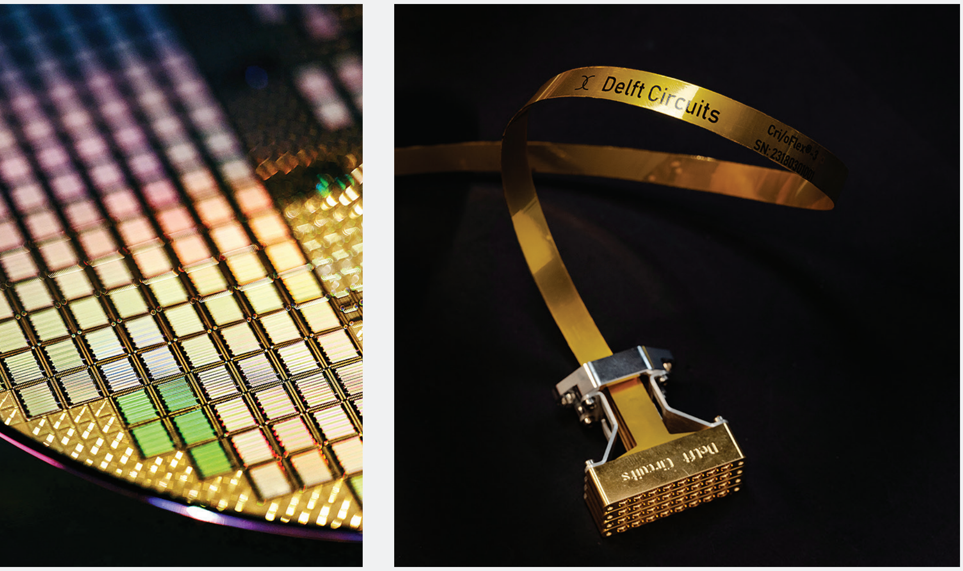
Signal amplifiers are another major source of heat for quantum computers. The output signals from qubits are extremely weak, which means that they need to be amplified considerably before they can be processed by conventional electronics. There are already superconducting signal amplifiers that generate very little heat and therefore can be placed alongside the qubits in the dilution refrigerator, says Jérôme Bourassa, the CEO of Canadian startup Qubic Technologies, but they don't provide enough of a boost to get the signals out of the fridge. That requires a second set of more powerful amplifiers that produce more heat in a separate section of the fridge held at 4 kelvins (about -269 °C).

However, as you increase the number of qubits, the number of required amplifiers increases in lockstep. "At some point, you reach a breaking point where you don't have enough cooling power accessible to remove the heat from the amplifiers," says Bourassa. "And so you are now stuck with a limited number of qubits in your fridge."

Qubic has created a novel superconducting amplifier made from a proprietary niobium alloy. Bourassa says that the design is able to boost signals to the same degree as the more powerful set of conventional amplifiers. But because it is superconducting like the first set of amplifiers, it reduces heat dissipation by a factor of 10,000.

> "You had first the few players who did everything, but then when things started speeding up, this was divided into many specialized sectors."
>
> —JANNE LEHTINEN, SEMIQON

FROM LEFT: SEMIQON; QUBIC TECHNOLOGIES; SEMIQON; DELFT CIRCUITS



As quantum computers mature, multiple companies are beginning to make available components designed specifically for quantum computers, including [from left] motherboards, signal amplifiers, CMOS wafers, and cabling.

That means these amplifiers can operate at millikelvin temperatures. However, Bourassa says the company's current designs produce too much noise to operate close to the qubits. So rather than replace both sets of existing amplifiers, Qubic plans to use its superconducting amplifiers as a replacement for the more powerful amplifiers that currently soak up much of the fridge's cooling budget. Qubic says it will have its amplifiers available this year.

The final culprit limiting the number of qubits in a single dilution refrigerator is the cabling. Most quantum computers rely on coaxial cables to send control signals to the qubits and readout signals away from them. These cables are bulky and feature a relatively thick metal wire at their core that can conduct heat into the system, says Daan Kuitenbrouwer, chief product officer at Delft Circuits.

Each time a cable connects with another component, it's another potential point of failure, says Kuitenbrouwer. Delft Circuits has developed a superconducting flex cable that is more compact, slashes the number of connections required, and significantly reduces the amount of heat the cables conduct into the fridge. Cables intended for the coldest parts of the dilution refrigerator are made from a niobium titanium superconductor, and in the 4-K portions, from silver. Because these wires are much thinner than those in coaxial cables, they conduct very little heat into the system, says Kuitenbrouwer.

Delft Circuits plans to use the same technology to eventually create what Kuitenbrouwer calls a "quantum motherboard"—a 2D sheet infused with connecting wires that can integrate various components at cryogenic temperatures. The company is banking on the notion that future quantum computers will follow a chiplet architecture with multiple smaller quantum processing units and cryogenic control electronics all integrated on the same chip.

"You get this whole zoo of different functional components that all have to be connected to each other," says Kuitenbrouwer. "So what you basically need is very high density, very low loss interconnect, and that is what superconducting flex can offer."

For Qubic's Bourassa, the only way the quantum industry is ever going to achieve the scale necessary to fulfill its lofty ambitions, however, is to tie all of these emerging components together to save space and cooling budgets. "Having the capacity to remove the heat, having the capacity to make your systems more compact is definitely the pathway towards something that is viable in the future, both in terms of power but also economically," he says. ■

CONSUMER ELECTRONICS

Researchers Study Better Shark Repellents

MOST SWIMMERS would prefer that sharks don't come near them. To this end, researchers in Australia are studying the nature of underwater electric fields to better deter sharks.

Sharks navigate and detect prey using electroreceptors in their snouts to track weak electric signals. But at certain thresholds, electric fields can also repel sharks, prompting some companies to develop wearable devices for swimmers. However, their effective range is limited, generally to within a couple of meters of the source.

In a study published in October in *IEEE Sensors Letters*, researchers took controlled measurements of underwater electric fields and developed a theoretical model to support the ongoing design of shark-repelling devices.

Their results underscore a major outstanding challenge—the rapid weakening of underwater electric fields—but also hint at ways to boost the range of future devices by optimizing electrode configuration, waveform design, and power delivery.

Coauthors Hugo Espinosa and David Thiel from Griffith University in Brisbane, Australia, also envision that a network of shark-repelling nodes along beaches could create larger protective zones someday.

—Michelle Hampson

BIOMEDICAL

For Glucose Monitors, Accuracy Claims Outpace Reality >

Real-world users call out marketing hype

BY GWENDOLYN RAK

In early 2023, San Diego–based health care company Dexcom had just begun shipping its seventh-generation continuous glucose monitor, aptly named the G7, in the United States. Dexcom claimed the G7 to be the "most accurate sensor" available to the thousands of people with Type 1 diabetes who use continuous glucose monitors to help manage their blood sugars.

But Dan Heller, who has diabetes, found that the G7's real-world performance wasn't up to par. In a September 2023 post on his Substack, which covers Type 1 diabetes research and management, he wrote about his own experience of comparing the G7 to the previous generation, the G6. Heller predicted an increase in adverse events with the G7, drawing on his past experience leading tech and biotech companies.

In the two years since Heller's experiment, many other users have reported issues with the device. Some complaints regard failed connection and deployment issues, which Dexcom claims to have now addressed. More concerning are reports of erratic, inaccurate readings. A public Facebook group dedicated to sharing negative experiences with the G7 now has tens of thousands of members, and several class action lawsuits have been filed against the company about the device's accuracy.

Yet based on a standard metric in the industry, the G7 is one of the most accurate glucose sensors available. "Accuracy in the performance of our device is our No. 1 priority. We understand this is a lifesaving device for people with Type 1 diabetes," says Peter Simpson, Dexcom's senior vice president of innovation and sensor technology. Simpson acknowledged some variability in individual sensors, but stood by the accuracy of the devices.

So why have users faced issues? In part, metrics used in marketing can be misleading compared to real-world performance. Differences in study design, combined with complex biological realities, mean that the accuracy of these biosensors can't be boiled down to one number—and users are learning this the hard way.

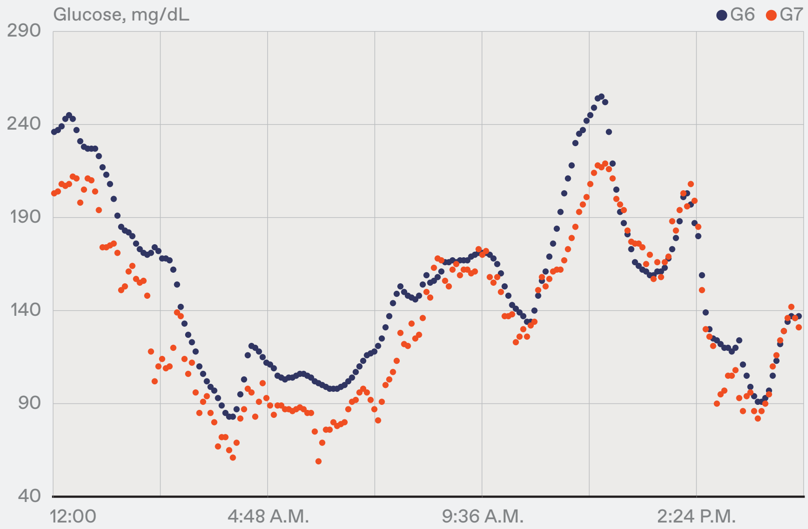
Continuous glucose monitors (CGMs) are sensors typically worn on the upper arm and consist of a small filament inserted under the skin and a transmitter that connects to an insulin pump, smartphone, or other device. The filament is coated with an enzyme that generates an electrical signal when it reacts with glucose in the fluid surrounding the body's cells. That signal is then converted to a digital signal and processed to generate glucose readings every few minutes. Each sensor lasts a week or two before needing to be replaced.

In the 2010s, CGMs required blood-glucose calibrations twice a

Dexcom touts its G7 sensor as the most accurate continuous glucose monitor available, but users have struggled with inconsistent readings.

DEXCOM

day and still weren't reliable enough to dose insulin based on the readings. Now, some insulin pumps use the near-real-time data to automatically make adjustments. With those improvements has come greater trust in the data users receive—and higher standards. A faulty reading could result in a dangerous dose of insulin.



When Dan Heller wore the Dexcom G6 and G7 at the same time, he says he noticed the G7 readings were more erratic, making it more difficult to properly control his blood sugar.

DAN HELLER

The G7 introduced several changes to Dexcom's earlier designs, including a much smaller footprint, and updated the algorithm used to translate sensor signals into glucose readings for better accuracy, Simpson says. "From a performance perspective, we did demonstrate in a clinical trial that the G7 is significantly more accurate than the G6," he says.

So Heller and others were surprised when the new Dexcom sensor seemed to be performing worse. For some batches of sensors, it's possible that the issue was in part due to an unvalidated change in a component used in a resistive layer of the sensors. The new component showed worse performance, according to a warning letter issued by the U.S. Food and Drug Administration in March 2025, following an audit of two U.S. manufacturing sites. The material has since been removed from all G7 sensors, Simpson says, and the company is continuing to work with the FDA to address concerns.

"There is a distribution of accuracies that have to do with people's physiology and also the devices themselves. Even in our clinical studies, we saw some that were really precise and some that had a little bit of inaccuracy to them," says Simpson. "But in general, our sensor is very accurate."

In late November, Abbott—one of Dexcom's main competitors—recalled some of its CGMs due to inaccurate low glucose readings. The recall affects approximately 3 million sensors and was caused by an issue with one of Abbott's production lines.

The accuracy of these biosensors can't be boiled down to one number—and users are learning this the hard way.

The discrepancy between reported accuracy and user experience, however, goes beyond any one company's manufacturing missteps. The accuracy of CGM systems is frequently measured via mean absolute relative difference, or MARD, a percentage that compares the sensor readings to laboratory blood-glucose measurements. The lower the MARD, the more accurate the sensor.

This number is often used in advertising and marketing, and it has a historical relevance, says Manuel Eichenlaub, a biomedical engineer at the Institute for Diabetes Technology at the University of Ulm, in Germany, where he and his colleagues conduct independent CGM performance studies. For years, there was a general belief that a MARD under 10 percent meant a system would be accurate enough to be used for insulin dosing.

But the way studies are designed can make a big difference. Glucose levels vary across the body, so the amount in blood collected from capillaries with a finger prick fluctuates more and can be around 5 to 10 percent higher than that in venous blood.

Additionally, the distribution of sampling isn't standardized. CGMs are known to be less accurate at the beginning and end of their lifespan, or when glucose levels are out of range or changing quickly. Simpson says that Dexcom's trial protocol tests the devices in different blood sugar ranges across the life of the sensor.

Dexcom and other companies advertise a MARD of around 8 percent. But some independent studies are more demanding and find higher percentages; a head-to-head study of three popular CGMs that Eichenlaub led found MARD values closer to 10 percent or higher.

Eichenlaub and other experts believe that more standardization of testing and an extension of the FDA requirements around insulin-guiding glucose monitors are necessary, and so they recently proposed comprehensive guidelines on CGM performance testing. As new companies enter the growing CGM market, "having a standardized way of evaluating the performance of those systems is very important," says Eichenlaub.

For users like Heller though, better accuracy matters only if it yields better diabetes management. He encourages engineers working on these devices to think like the patient. "At some point, there's quantitative data, but you need qualitative data," he says. "I don't care about MARD. I want data that is reliably *actionable*." ■

VERSE BECOMES ELECTRIC

BY PAUL JONES

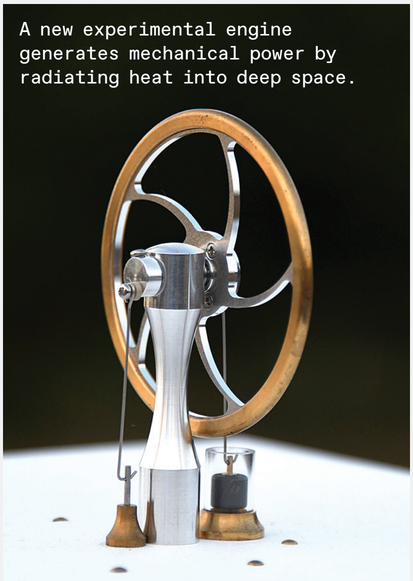
Ode to Very Small Devices

As fairies for the Irish or leeks for Welsh,
it's the secret lives of small hidden machines,
their junctures, and networks that inspire me:
Mystic hidden functionaries that make
our made world live, brave little servo motors,
whose couplers, whose eccentric fire-filled
sensors are encased in bakelite with brass
screws, who stare with red eyes, who gauge moisture,
who notice tiny motions and respond,
whose cooling fans call out in white-noise
registers like older folk singers–I can
almost hear their earlier songs, their strong voices
now yelps, their thumps, their throbs, their hum, their chant–,
they click, they whir, they are sent spinning
inside like teen girls giggling over boy bands.
Most of all: ones waiting silently, concealing
the surprise of their purpose, tasks not yet known,
their true natures found only in connections.

Those that listen, those that speak,
those that control cool and heat,
those that open doors, those that lock
all the things that we've forgot,
those that hide, those that disclose
those embedded in our clothes
those in our ears, those in our hearts
those that bring together, those a part
of divisions, those like birds,
like parrots that complete our words,
those like fish, those that entrap,
those that free, those that freely flap
in fierce winds, those that replace
what we have lost, those that see
at night, in fog, in brightness, in fear,
those that show what we hold dear,
those that tempt, those that repel,
those that buy and those that sell,
those that keep us alive, those that
don't, won't, couldn't and cannot.

Parts of one mind, not mine, blunt orchestra
of information, bundles of feelers
reaching out to touch us, teach us, guide us
to form better futures better understood.
May your sounds, your chimes, your silence calm us.
May your tender tendrils touch what we seek.
Small parts becoming one being intertwined,
a world in itself, remind us to be kind.

Paul Jones, inducted into the NC State Computer Science Hall of Fame in 2021, has published two poetry collections, and manuscripts of his poems have traveled to the moon on missions in 2019 and 2024.



A new experimental engine generates mechanical power by radiating heat into deep space.

JEREMY MUNDAY

ENERGY

Engine Generates Power by Beaming Heat into Space

> It's a new spin on an 1800s invention

BY CHARLES Q. CHOI

A decade ago, scientists at Stanford University invented superthin materials that could provide cooling by beaming heat into outer space. The technique, a form of radiative cooling, involves emitting heat as wavelengths of infrared radiation between 8 and 13 micrometers. The atmosphere does not absorb these particular wavelengths, so they transfer energy directly into the vacuum of space.

In a new effort, researchers from the University of California, Davis, have developed a variation on the idea by using radiative cooling to chill a Stirling engine below ambient temperature to produce mechanical and electrical power. "With more efficient engine designs, we think this approach could enable a new class of passive, around-the-clock power systems that complement solar energy and help support resilient, off-grid infrastructure," says Jeremy Munday, a professor of electrical and computer engineering at UC Davis.

Stirling engines have been around since the early 1800s. At the heart of a Stirling engine is a gas sealed in an airtight chamber. When the gas is heated, it expands and pressure increases within the chamber; when it is cooled, it contracts, reducing pressure. Repeatedly heating and cooling the gas creates a cycle of expansion and contraction that drives a piston, generating power. These engines can also directly produce mechanical power to circulate air or pump water.

Munday and his colleagues connected a Stirling engine to a heat-radiating antenna in the form of a 300-by-300-millimeter metal plate covered in emissive paints. The antenna cools the Stirling engine to below ambient temperature, reducing the engine's internal gas pressure. The gas then expands due to ambient heat, creating a continuous power cycle.

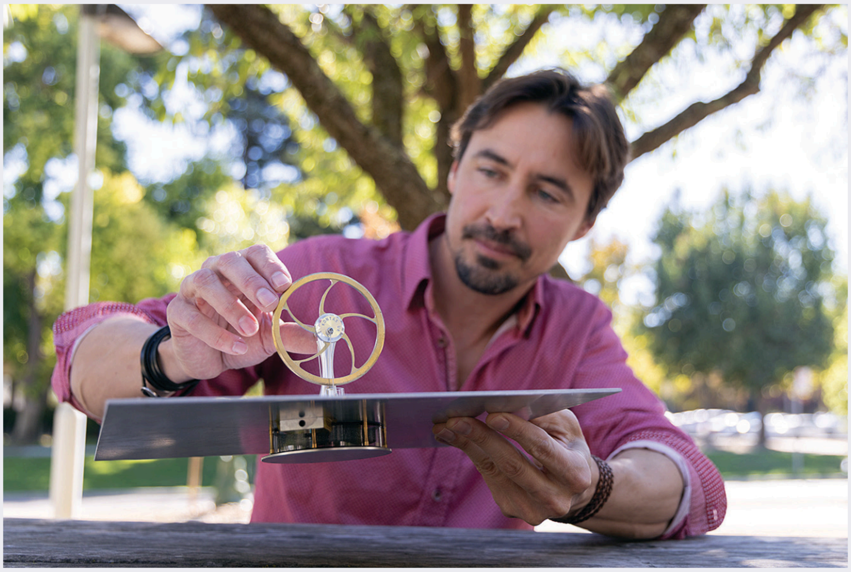
A year of nighttime experiments revealed that the device could usually generate more than 10 °C of cooling. The Stirling engine harnessed that cooling to produce more than 400 milliwatts of mechanical power per square meter—enough to directly power a fan or generate current from a small electric motor. The scientists detailed their findings in November in *Science Advances*.

Because the source of the device's energy is Earth's ambient heat instead of the sun's heat, its power output "is much lower than [that of] solar photovoltaics—roughly two orders of magnitude lower," Munday says. "However, the goal is not to replace solar. Instead, this enables useful work when solar power is unavailable, such as at night."

The researchers calculated the device could generate more than 5 cubic feet per minute of airflow, the minimum airflow rate the American Society of Heating, Refrigerating and Air-Conditioning Engineers requires to minimize detrimental effects on health inside public buildings. Potential applications may include circulating carbon dioxide within greenhouses to promote plant growth and improving comfort inside residential buildings.

Munday says that the researchers would like to set up their devices in a greenhouse as a proof-of-concept application. They're also interested in engineering the device to work during the day. That would require the engine to reflect incoming solar radiation in addition to emitting infrared radiation to avoid being heated by the sun's energy.

The researchers see plenty of options to improve the device's performance. For example, they say that they could replace the air sealed inside the engine with hydrogen or helium gas to reduce internal friction. ■



Jeremy Munday holds a large metal plate that acts as a heat-radiating antenna to heat and cool a gas chamber. The pressure changes drive a mechanical piston (not shown).

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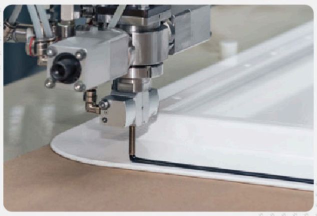

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The Data

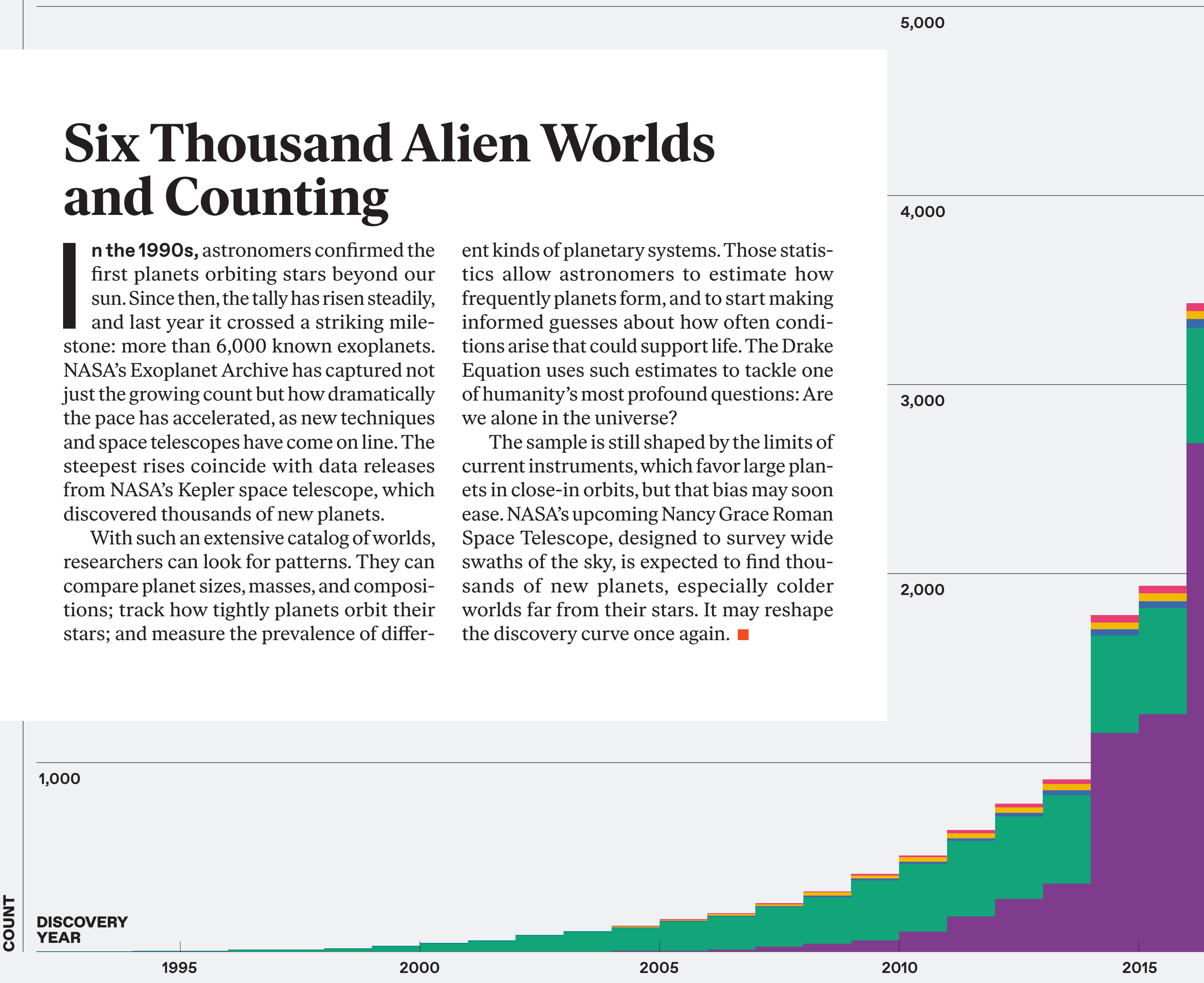
Most Common Methods of Discovery

🟪 **TRANSITS** Astronomers detect a planet when it passes in front of its star, causing a tiny, regular dip in the star's brightness. This method has found the vast majority of known exoplanets.

🟩 **RADIAL VELOCITY** A planet's gravity makes its star wobble slightly, shifting the star's light toward red and blue wavelengths. Measuring that wobble reveals a planet's minimum mass and orbit.

🟦 **MICROLENSING** When a star passes in front of a more distant star, its gravity briefly magnifies the background light; an orbiting planet can create a telltale blip in that signal. The technique is especially good at finding cold planets far from their stars.

🟨 **DIRECT IMAGING** Astronomers block out a star's light to capture faint images of planets orbiting nearby. It's rare, but it can reveal young, massive planets and allow direct study of their atmospheres.



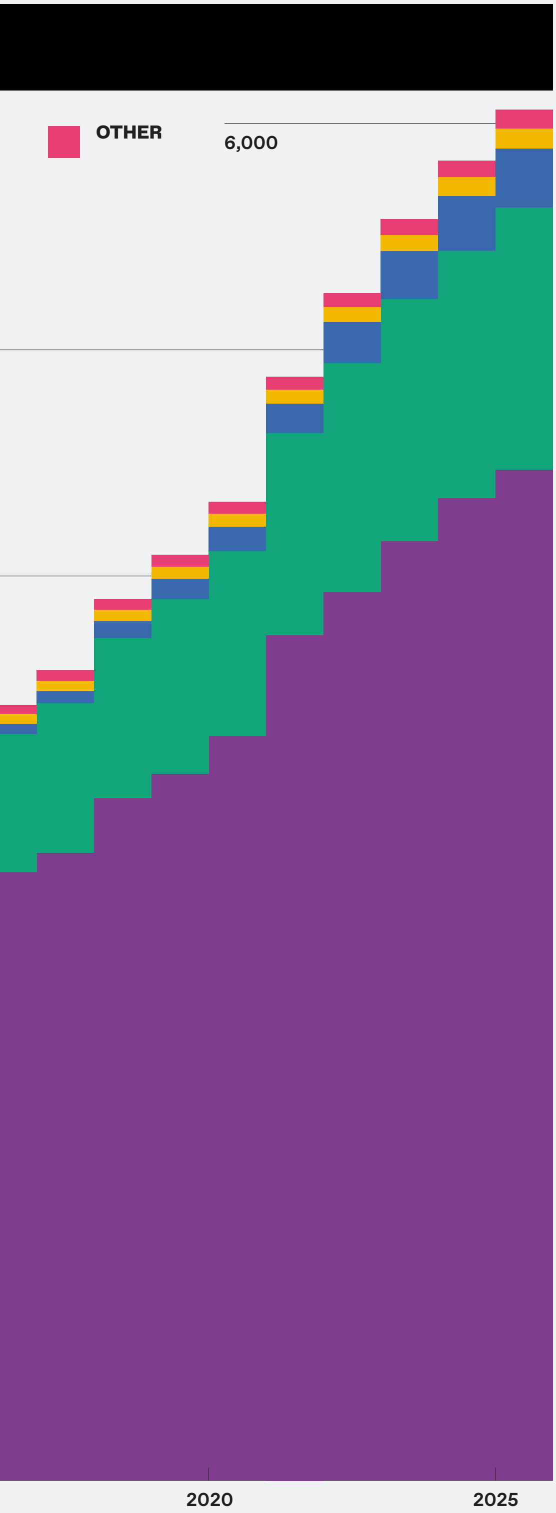
Six Thousand Alien Worlds and Counting

In the 1990s, astronomers confirmed the first planets orbiting stars beyond our sun. Since then, the tally has risen steadily, and last year it crossed a striking milestone: more than 6,000 known exoplanets. NASA's Exoplanet Archive has captured not just the growing count but how dramatically the pace has accelerated, as new techniques and space telescopes have come on line. The steepest rises coincide with data releases from NASA's Kepler space telescope, which discovered thousands of new planets.

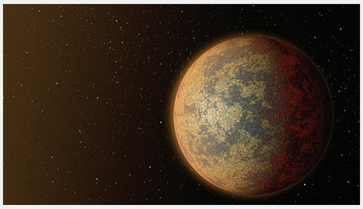
With such an extensive catalog of worlds, researchers can look for patterns. They can compare planet sizes, masses, and compositions; track how tightly planets orbit their stars; and measure the prevalence of different kinds of planetary systems. Those statistics allow astronomers to estimate how frequently planets form, and to start making informed guesses about how often conditions arise that could support life. The Drake Equation uses such estimates to tackle one of humanity's most profound questions: Are we alone in the universe?

The sample is still shaped by the limits of current instruments, which favor large planets in close-in orbits, but that bias may soon ease. NASA's upcoming Nancy Grace Roman Space Telescope, designed to survey wide swaths of the sky, is expected to find thousands of new planets, especially colder worlds far from their stars. It may reshape the discovery curve once again. ■

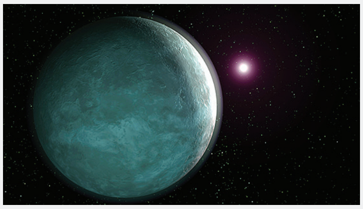
BY ELIZA STRICKLAND



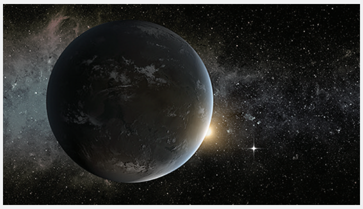
Types of Planets Discovered



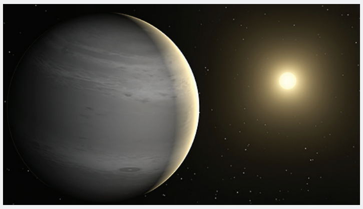
TERRESTRIAL
These small, dense worlds are made mostly of rock and metal and are comparable in size to Earth or Mars. They can have widely varying temperatures and atmospheres, and some may ultimately prove capable of hosting liquid water.



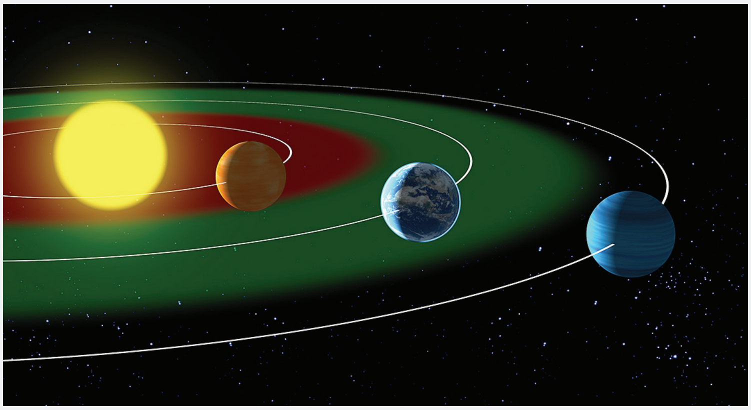
NEPTUNE-LIKE
These planets are similar in size to Neptune and have thick atmospheres rich in hydrogen and helium surrounding denser, ice-rich interiors. They are larger than super-Earths but far less massive than gas giants.



SUPER-EARTH
These planets are larger than Earth but smaller than Neptune and span a wide range of compositions, from rocky worlds with thick atmospheres to gas-rich planets. They are among the most common exoplanets and have no direct counterparts in our solar system.



GAS GIANT
These massive planets are dominated by hydrogen and helium and lack a solid surface, like Jupiter and Saturn. Some orbit extremely close to their stars as “hot Jupiters,” while others circle at much greater distances.



THE “GOLDILOCKS ZONE” [green] is the range of distances from a star where temperatures could allow liquid water to exist on a planet’s surface, depending on the star’s size and brightness. Liquid water is considered essential for life as we know it.

JPL-CALTECH/NASA (TOP 4)

“Goldilocks zone” illustration by John MacNeill

TECH TO TINKER WITH

Hands On

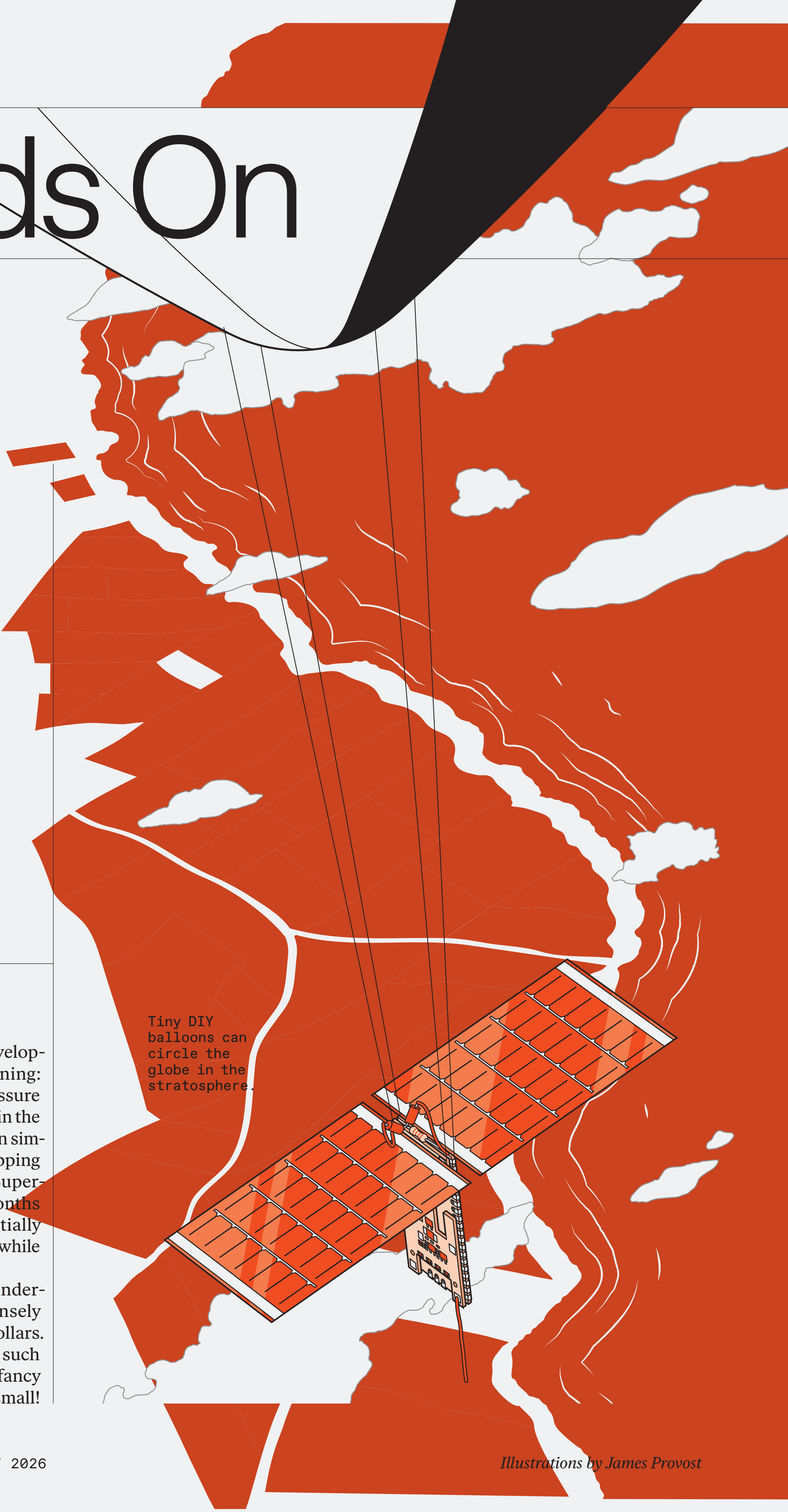
Long-Duration Amateur Ballooning

› Send a pico balloon into the stratosphere and track it globally

BY DAVID SCHNEIDER

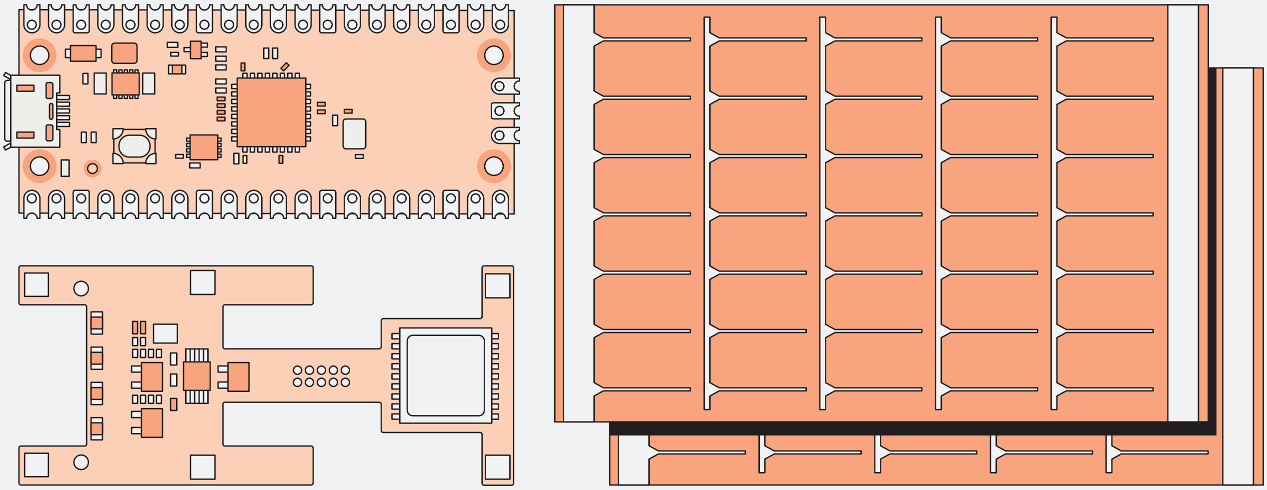
There's an interesting development in amateur ballooning: using so-called superpressure balloons, which float high in the atmosphere indefinitely rather than simply going up and up and then popping like a normal weather balloon. Superpressure balloons can last for months and travel long distances, potentially circumnavigating the globe, all the while reporting their position.

You might imagine that an undertaking like this would be immensely difficult and cost thousands of dollars. In fact, you can build and launch such a balloon for about the cost of a fancy dinner out. You just have to think small!



Tiny DIY balloons can circle the globe in the stratosphere.

Illustrations by James Provost



A Raspberry Pi Pico microcontroller [top left] is soldered directly to a daughterboard consisting of a high-frequency transmitter and a GPS module [bottom left], which are all powered by solar panels [right].

That's why amateur balloonists call them pico balloons.

The payload of a pico balloon is so light (between 12 to 30 grams) that you can use a large Mylar party balloon filled with helium to lift it. They're also inexpensive; that's important because you won't get your payload back. And because such diminutive payloads don't pose a danger to aircraft, they aren't subject to the many rules and restrictions on free-floating balloons that carry more mass.

The essential advances that made pico ballooning possible were figuring out how to track a balloon no matter where in the world it might be and how to power such tiny payloads. A lot of folks worked on these challenges and came up with good solutions that aren't hard or expensive to reproduce.

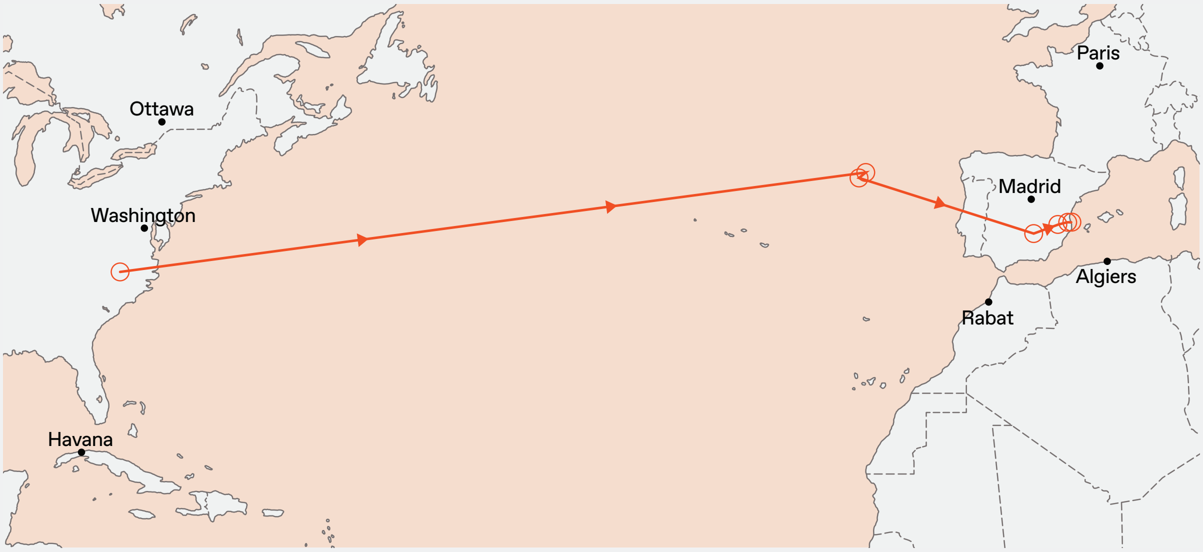
Amazingly, the global tracking of the balloon's telemetry is done without satellites. Instead, pico balloonists take advantage of an amateur-radio network called WSPR (Weak Signal Propagation Reporter), a protocol developed by a rather famous ham-radio enthusiast—Joseph Hooton Taylor Jr., one of the two scientists awarded the 1993 Nobel Prize in Physics for discovering binary pulsars.

WSPR was designed to monitor signal-propagation conditions for different radio bands—useful information if you're a ham trying to make distant contacts. WSPR can also record low-power balloon-telemetry signals. WSPR is very low bandwidth—less than 10 bits per minute—but it does the job. A worldwide network of radio amateurs receives these WSPR signals and reports them publicly over the internet, which gives pico balloonists a way to track their flights. You need at least a general-class ham-radio license to launch a pico balloon, as one is required to transmit on the bands used for long-distance telemetry.

The pico balloon payload I chose to build is based on the aptly named US $4 Raspberry Pi Pico board, with a solder-on daughterboard that contains a GPS receiver and transmitter. The folks who developed this daughterboard and associated software (to create what they call the Jetpack WSPR Tracker) have done a fantastic job of making their work easy to reproduce.

You could, in principle, power the Jetpack tracker with batteries, but in practice it would be impossible to keep them warm in the stratosphere, where average temperatures can be as low as –51 °C. Instead, the tracker runs off two lightweight solar modules. At night, it gracefully powers down. When the sun rises high enough in the morning, the tracker powers up and starts transmitting again.

I had five Jetpack boards custom-manufactured in China for just $39. The cost nearly doubled after adding shipping and tariff charges. Still, that's really cheap, even when you add the cost of the Raspberry Pi ($4), the party balloon ($10 for two), the helium ($10 at my local



The WSPR network tracked my balloon from the Eastern United States to the Mediterranean coast.

supermarket), and the two solar modules ($7 each).

The biggest sticking point I had with the Jetpack design was the liberties it takes with spurious emissions from its transmitter. Federal Communications Commission (FCC) regulations call for spurious emissions to be at least 43 decibels below the power of the transmitted signal. But my transmitter had strong unwanted emissions at odd harmonics of the fundamental frequency. (That's because the transmitter is a Si5351A temperature-controlled oscillator, which outputs a square wave, not a sinusoid.) Taking measurements, I could see that the third harmonic at 42 megahertz was only 25 dB quieter than the 14-MHz fundamental of my WSPR signal's frequency.

In practical terms, this shouldn't create any noticeable interference, given that this transmitter puts out milliwatts at most and floats kilometers away from the nearest receiver. Still, I wanted to be fully compliant with FCC regulations, so I added traps to the antenna—simple circuit elements that hams use to allow a single antenna to work on multiple bands by altering how the antenna resonates at different frequencies. Each trap was made of a small inductor (four 5-millimeter-diameter loops of No. 32 magnet wire) in parallel with a 220-picofarad capacitor. I tuned them with the help of a NanoVNA signal analyzer by stretching the loops apart slightly. I attached the traps directly to the tracker board, so that they quashed the spurious 42-MHz emissions at the source. That worked well and added only 0.3 grams of weight.

With my payload complete, I partially filled my balloon with helium. You want the balloon to hold just a little more gas than it takes to lift the payload off the ground. This will give the helium room to expand as the balloon climbs to its final altitude.

My first pico balloon, launched from a park near my home in North Carolina, made it only halfway across the Atlantic before going silent. My second went up and was never heard from again. The third was indeed the charm. It crossed the Iberian Peninsula and at the time of this writing is somewhere over the Mediterranean at an altitude of nearly 12 kilometers. It's possible it could go on to orbit the planet.

I'm a little puzzled about the balloons' telemetry messages received on the WSPR network, as they have been few and far between. My best guess is that power from the horizontal solar panels I'm using is marginal, with the winter sun being so low in the sky. That's something I should have thought about before launching the first balloon just 24 hours after the winter solstice! ■

My first pico balloon made it only halfway across the Atlantic before going silent.

BY NOVID PARSI

Careers

Carlotta Berry

This professor is bringing open-source robotics to the streets

Carlotta Berry holds a modified STEMBot, a robot originally designed by a team at the University of Nebraska Omaha.

As a math and engineering student in the 1980s and '90s, Carlotta Berry had two experiences that helped shape her future as an educator.

First, although she studied robots, she wasn't allowed to interact with them. "The robots were too expensive, so the undergrads did not get to touch them," Berry recalls. "I said to myself, I'm going to teach engineering someday, but in a way that the students will get to touch and program the robot."

This led Berry to work toward overcoming the economic exclusivity of robotics. But her second formative undergrad experience involved a different type of exclusion: Berry was one of only a few engineering students who were female or Black. "It sometimes could be a lonely experience," says Berry. "Representation does matter."

Now, Berry is a professor in the electrical and computer engineering department at Rose-Hulman Institute of Technology, in Terre Haute, Ind., where her students learn about human-robot interactions and mobile robotics by using actual robots.

She also works to support people of color in engineering. Almost three decades after she graduated, Berry realized little progress had been made when she heard Black women grad students describe feeling isolated and marginalized during an online engineering conference in 2020. "This was exactly how I felt 30 years ago," says Berry, noting that today only about 8 percent of electronics engineers are women and about 5 percent are Black. "It was time for something to change."

As a child in Nashville, Berry excelled at school—especially math—and thought she'd become a math teacher. But in high school, a mentor suggested that Berry consider engineering, given her strong grades in both math and science. "I didn't really know what an engineer was," she recalls. "I didn't know anyone who was an engineer." After learning about the profession at a library, she decided to study both engineering and math in college. In 1993, Berry earned a bachelor's in electrical engineering at Georgia Tech, in Atlanta, as part of a dual-degree program with Spelman College, where she earned a bachelor's in mathematics in 1992.

> **"When I provide education for students and for the community, that's also part of my research and service."**

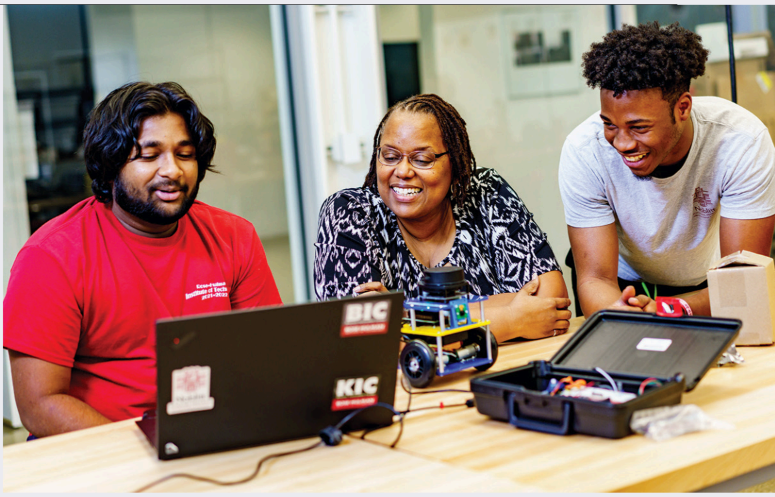
After completing her bachelor's degrees, Berry worked as a control engineer for Ford Motor Co., where she programmed assembly-line industrial robots, but she found herself yearning to answer her true calling as an educator. So she returned to academia and got a master's in electrical engineering with an emphasis on control systems at Wayne State University, in Detroit, in 1996. Saddled with student loan debt, however, Berry then accepted a position as a controls engineer for Detroit Edison. "I really enjoyed the work but once again realized I was not doing what I was meant to do," she says.

After a year at Detroit Edison, she left in pursuit of her Ph.D. in electrical and computer engineering, which she earned at Vanderbilt University, in Nashville, in 2003. As a grad student, Berry taught at a technical school—and at last found herself on the right career path: "I always wanted to be an educator," she says.

Berry traces her community-outreach work to two more pivotal moments in her career: In 2018, she became a full professor at Rose-Hulman, and in 2020, she became an endowed chair in the electrical and computer engineering department. Berry says her tenure and position at Rose-Hulman enables her to pursue work that brings her research, teaching, and service interests together.

As a full professor, Berry says she doesn't have to worry about whether others perceive her outreach work as less important than her technical

HALEY ROSE PHOTOGRAPHY



Berry works on her first open-source modular 3D-printed robot, the LilyBot, with Rose-Hulman engineering students Murari Srinivasan [left] and Josiah McGee [right].

robotics work. "When I provide education for students and for the community, that's also part of my research and service," she says. For Berry, research and service are not separate but intertwined: Her research involves designing open-source, low-cost mobile robots to promote more-inclusive robotics education.

Since 2020, Berry has helped transform how electrical and computer engineering is taught and perceived. Through hands-on lessons, she has been teaching robotics not only to her students at Rose-Hulman but also to kids and adults across the nation. Berry has been taking her robots, as she says, "to the streets."

Berry demonstrates and discusses her open-source, 3D-printed wheeled robots at schools, libraries, museums, and other community venues. Her audiences range from kids just a few years old to adult educators who learn about robotics from Berry so they can teach the subject to their own students. To spread the word about robotics and STEM, Berry also has become active on social media, overcoming her innate introversion because, she explains, "visibility matters."

With any audience, Berry is always "very approachable and very engaging," says Nicki Manion, a program manager for Rose-Hulman's educational outreach who collaborates with Berry on professional development workshops for teachers.

"I have to go where people are," Berry says. "I get robots in front of people who are historically marginalized and would normally not have access to these technologies."

This past summer, for example, Berry shared her robots with children from about 3 to 10 years old at dozens of branches of the Indianapolis Public Library. To understand the three main pillars of robotics—sense, plan, act—the kids learned how the robots use sonar, a microphone, and a speaker in order to see, hear, and talk. Notably, at the end of each presentation, the kids got to play with the robots.

Last year, as part of an IEEE Education Society initiative, Berry brought her robots to the streets in other countries. After grad students in countries such as Costa Rica, Niger, and Uganda received parts in the mail, Berry showed them the basics of building and programming robots.

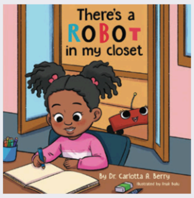
Berry hasn't set out on her pedagogic journey all on her own, she says. In 2020, she cofounded Black in Engineering and Black in Robotics—part of the Black in X network comprising more than 80 organizations that support the work of Black professionals in STEM. For Berry, it's no coincidence that Black in X emerged early in the pandemic. "There were a lot of bad things about the pandemic, but because we were all home and on social media, we were able to connect and find each other and form these organizations that, five years later, are still going," she says.

Her professional pivot toward more community-oriented service has led to several accolades, she says: "That was when I started to earn these awards I had never been considered for before." In 2023, the IEEE Robotics and Automation Society awarded Berry the prestigious Undergraduate Teaching Award for her contributions to multidisciplinary robotics education and leadership in diversifying STEM. She has also been recognized by the Society of Women Engineers and AnitaB.org.

On top of her outreach and community work, Berry finds time to write children's books—work that also has its roots in the pandemic. During that time, Berry woke up from a dream and remembered only the title of a children's book she knew she had to write: "There's a Robot in My Closet." The book spawned a series, which features kid protagonists learning how to program robots and developing their problem-solving skills. (Berry also writes STEM-centered romance novels for adults under the pseudonym Carlotta Ardell. The heroine of her book *Elevated Inferno: Monet's Moment* (2022), Berry says, struggles with the expectation to flawlessly juggle work and life—an expectation that falls more heavily on women, she finds.)

While balancing her many personal and professional interests, Berry says, she maintains a clear-eyed pursuit of her professional mission: helping people of diverse backgrounds "see themselves as not just consumers of technology but creators of technology."

For more on robots for STEM education, check out *IEEE Spectrum's* Robots Guide at robotsguide.com. ■



Children's books like those in Berry's *There's a Robot!* series help get kids interested in STEM.

Employer:
Rose-Hulman Institute of Technology

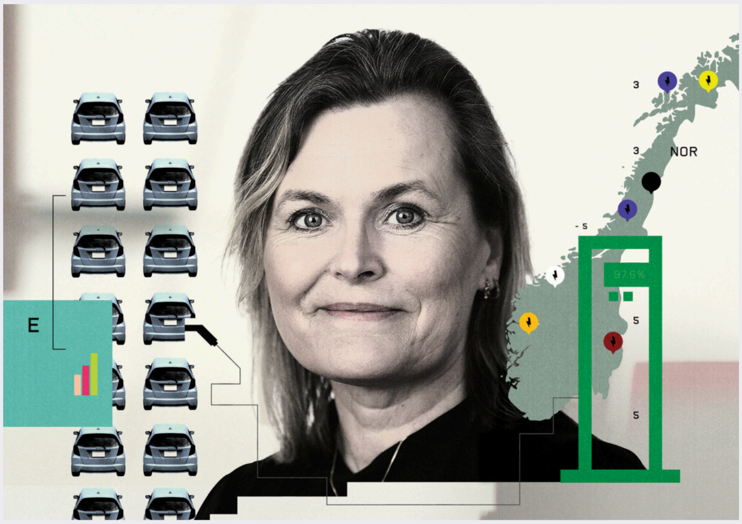
Occupation:
Professor of electrical and computer engineering

Education:
Bachelor's degree in mathematics, Spelman College; bachelor's degree in electrical engineering, Georgia Tech; Ph.D. in electrical and computer engineering, Vanderbilt University

TOP: BRYAN CANTWELL/ROSE-HULMAN INSTITUTE OF TECHNOLOGY; BOTTOM: REBELLION LIT

BY LUCAS LAURSEN

5 Questions



Cecilie Knibe Kroglund is the state secretary in Norway's Ministry of Transport.

Cecilie Knibe Kroglund

How Norway successfully navigated the EV transition

More than 97 percent of the new cars Norwegians registered in November 2025 were electric, almost reaching the country's goal of 100 percent. As a result, the government has begun removing some of the many carrots it used to encourage its successful EV transition. Cecilie Knibe Kroglund, state secretary in the country's Ministry of Transport, reveals some of the challenges that come with success.

How did Norway first promote EVs?
Kroglund: Battery-electric vehicles have had exemptions from the 25 percent value-added tax and from the CO_2- and weight-based registration tax that apply to combustion-engine vehicles. We used other tax incentives to encourage building charging stations on highways and in rural areas. Cities had the opportunity to exempt zero-emissions cars from toll roads. EV drivers also got reduced ferry fares, free parking, and access to bus lanes in many cities. The technology for the vehicles wasn't that good at the start of the incentives program, but we had the taxes and incentives to make traditional passenger cars more expensive.

How did policymakers overcome adoption barriers?
Kroglund: Early on the technology was challenging. In summertime it was easy to fuel the EV, but in wintertime it's double the use of energy. But the technology has improved a lot in the last five years.

The Norwegian tax exemptions on EVs were introduced before EVs came to market and were decisive in offsetting the early disadvantages of EVs compared to conventional cars, especially regarding comfort, vehicle size, and range. The rapid expansion of charging infrastructure along major corridors has also been important to overcome range anxiety.

How did the private sector respond?
Kroglund: Many Norwegian companies use EVs. The market for charging infrastructure is considered commercially viable and no longer needs financial support. However, we don't see commercial-vehicle adoption going as fast as passenger vehicles, and we had the same goal. So we will have to review the goals, and we'll have to review the incentives.

How did success create new problems?
Kroglund: The success of the passenger-vehicle policies mean EVs are in competition with public transport in the larger cities. Driving an EV remains much cheaper than driving a conventional car even without tax exemptions, and overall car use continues to rise. National, regional, and local governments must find different tools to promote walking, bicycling, and public transport because each city and region is different.

How widely applicable are these lessons?
Kroglund: We are different as countries. The geographies are different, and some countries have even bigger cities than our national population. This is not a policy for L.A., but what we see in Norway is that incentives work. However, tax incentives are only applicable in systems where effective taxation is established, which may not be the case in poorer countries. Other benefits, such as lower local emissions, only apply in places with lots of traffic.

The Norwegian experience shows that the economic incentives work, but it also shows that EVs work even in a country with cold weather. ■

SOURCE IMAGE: MORTEN BRAKESTAD

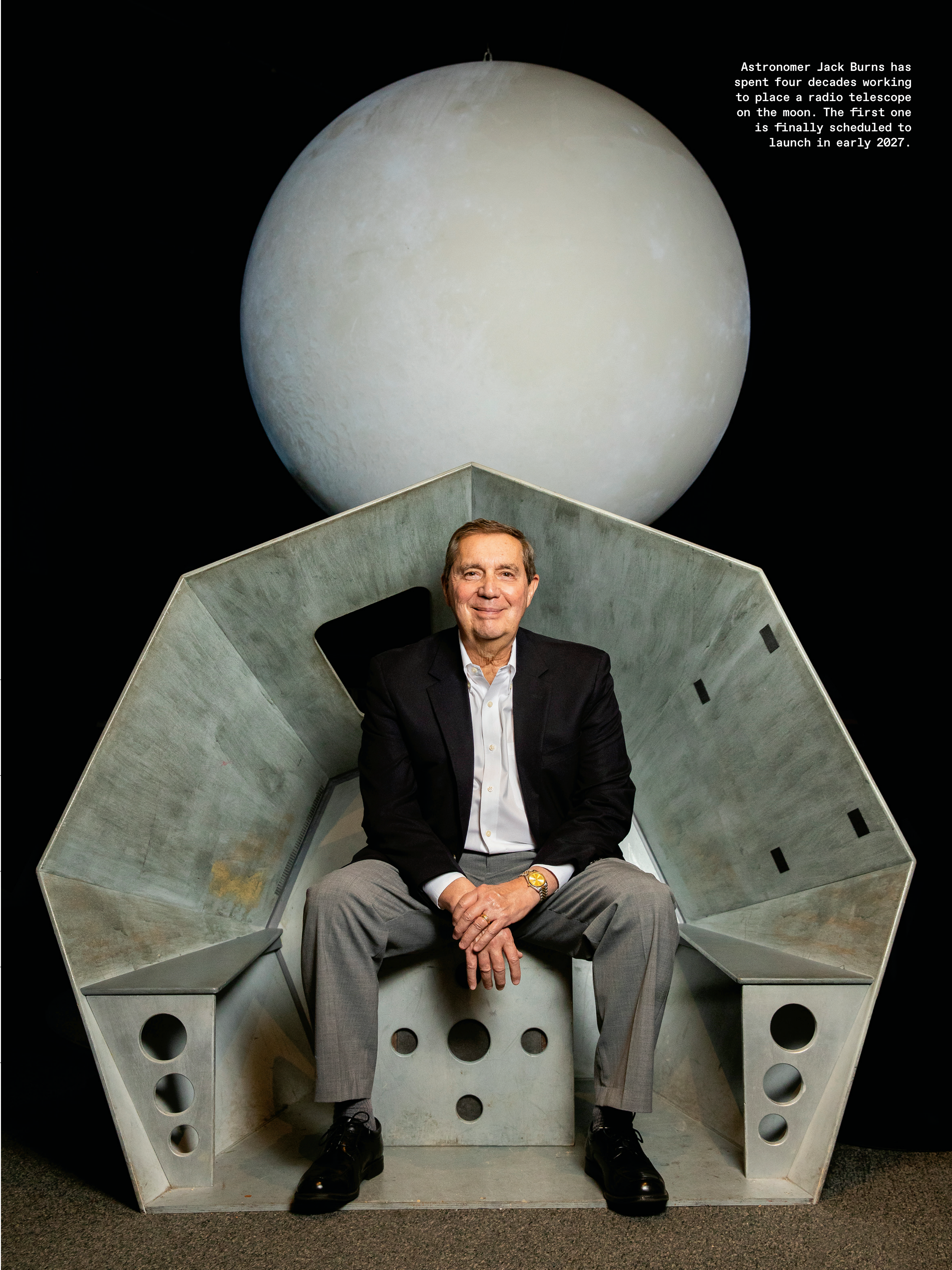
Photo-illustration by Stuart Bradford

THE **QUEST** TO BUILD A TELESCOPE THAT CAN HEAR THE COSMIC DARK AGES

THE CATCH: IT WILL HAVE TO BE ON THE MOON

By Ned Potter

Photo by David Williams



Astronomer Jack Burns has spent four decades working to place a radio telescope on the moon. The first one is finally scheduled to launch in early 2027.

↑ In an artist's rendering, the LuSEE-Night radio telescope sits atop Firefly Aerospace's Blue Ghost 2 lander, which will carry it to the moon's far side.

ISOLATION DICTATES WHERE WE GO TO SEE INTO THE FAR REACHES OF THE UNIVERSE. The Atacama Desert of Chile, the summit of Mauna Kea in Hawaii, the vast expanse of the Australian Outback—these are where astronomers and engineers have built the great observatories and radio telescopes of modern times. The skies are usually clear, the air is arid, and the electronic din of civilization is far away.

It was to one of these places, in the high desert of New Mexico, that a young astronomer named Jack Burns went to study radio jets and quasars far beyond the Milky Way. It was 1979, he was just out of grad school, and the Very Large Array, a constellation of 28 giant dish antennas on an open plain, was a new mecca of radio astronomy.

But the VLA had its limitations—namely, that Earth's protective atmosphere and ionosphere blocked many parts of the electromagnetic spectrum, and that, even in a remote desert, earthly interference was never completely gone.

Could there be a better, even lonelier place to put a radio telescope? Sure, a NASA planetary scientist named Wendell Mendell, told Burns: How about the moon? He asked if Burns had ever thought about building one there.

"My immediate reaction was no. Maybe even hell, no. Why would I want to do that?" Burns recalls with a self-deprecating smile. His work at the VLA had gone well, he was fascinated by cosmology's big questions, and he didn't want to be slowed by the bureaucratic slog of getting funding to launch a new piece of hardware.

But Mendell suggested he do some research and speak at a conference on future lunar observatories, and Burns's thinking about a space-based radio telescope began to shift. That was in 1984. In the four decades since, he's published more than 500 peer-reviewed papers on radio astronomy. He's been an adviser to NASA, the Department of Energy, and the White House, as well as a professor and a university administrator. And while doing all that, Burns has had an ongoing second job of sorts, as a quietly persistent advocate for radio astronomy from space.

And early next year, if all goes well, a radio telescope for which he's a scientific investigator will be launched—not just into space, not just to the moon, but to the moon's far side, where it will observe things invisible from Earth.

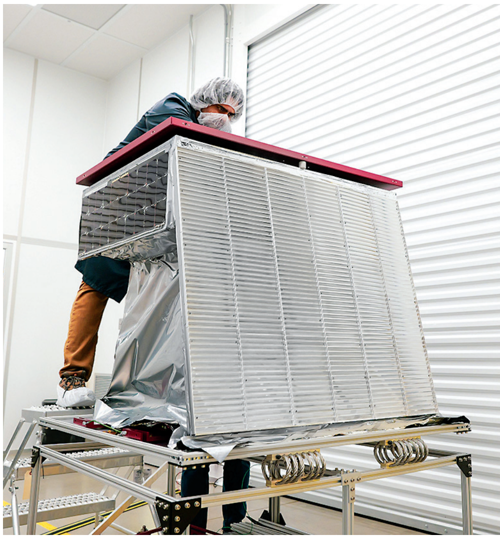
"You can see we don't lack for ambition after all these years," says Burns, now 73 and a professor emeritus of astrophysics at the University of Colorado Boulder.

The instrument is called LuSEE-Night, short for Lunar Surface Electromagnetics Experiment–Night. It will be launched from Florida aboard a SpaceX rocket and carried to the moon's far side atop a squat four-legged robotic spacecraft called Blue Ghost Mission 2, built and operated by Firefly Aerospace of Cedar Park, Texas.

Landing will be risky: Blue Ghost 2 will be on its own, in a place that's out of the sight of ground controllers. But Firefly's Blue Ghost 1 pulled off the first successful landing by a private company on the moon's near side in March 2025. And Burns has already put hardware on the lunar surface, albeit with mixed results: An experiment he helped conceive was on board a lander called Odysseus, built by Houston-based Intuitive Machines, in 2024. Odysseus was damaged on landing, but Burns's experiment still returned some useful data.

Burns says he'd be bummed about that 2024 mission if there weren't so many more coming up. He's joined in proposing myriad designs for radio tele-

TOP LEFT: FIREFLY AEROSPACE; BOTTOM RIGHT: ARIZONA STATE UNIVERSITY/GSFC/NASA



FROM LEFT: SPACE SCIENCES LABORATORY/UNIVERSITY OF CALIFORNIA, BERKELEY (2); FIREFLY AEROSPACE

↑ LuSEE-Night undergoes final assembly [left and center] at the Space Sciences Laboratory at the University of California, Berkeley, and testing [right] at Firefly Aerospace outside Austin, Texas.

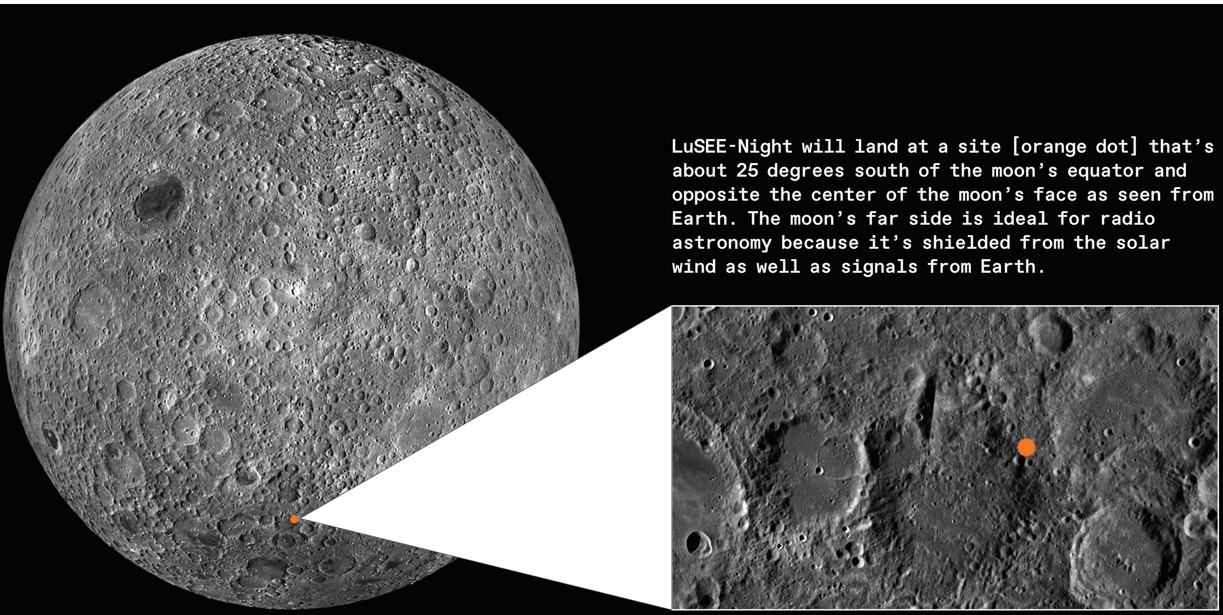
scopes that could go to the moon. And he's kept going through political disputes, technical delays, even a confrontation with cancer. Finally, finally, the effort is paying off.

"We're getting our feet into the lunar soil," says Burns, "and understanding what is possible with these radio telescopes in a place where we've never observed before."

A **MOON-BASED RADIO TELESCOPE** could help unravel some of the greatest mysteries in space science. Dark matter, dark energy, neutron stars, and gravitational waves could all come into better focus if observed from the moon. One of Burns's collaborators on LuSEE-Night, astronomer Gregg Hallinan of Caltech, would like such a telescope to further his research on electromagnetic activity around exoplanets, a possible measure of whether these distant worlds are habitable. Burns himself is especially interested in the cosmic dark ages, an epoch that began more than 13 billion years ago, just 380,000 years after the big bang. The young universe had cooled enough for neutral hydrogen atoms to form, which trapped the light of stars and galaxies. The dark ages lasted between 200 million and 400 million years.

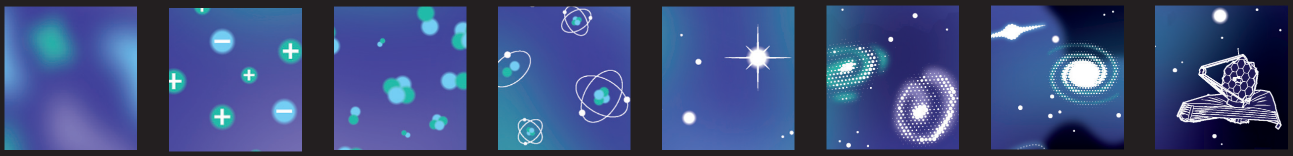
"It's a critical period in the history of the universe," says Burns. "But we have no data from it."

The problem is that residual radio signals from this epoch are very faint and easily drowned out by closer noise—in particular, our earthly communications networks, power grids, radar, and so forth. The sun adds its share, too. What's more, these signals have been dramatically redshifted by the expansion of the universe, their wavelengths stretched as their sources have sped away from us over billions of years. The most critical example is neutral hydrogen, the most abundant element in the universe, which when excited in the laboratory emits a radio signal with a wavelength of 21 centimeters. Indeed,



LuSEE-Night will land at a site [orange dot] that's about 25 degrees south of the moon's equator and opposite the center of the moon's face as seen from Earth. The moon's far side is ideal for radio astronomy because it's shielded from the solar wind as well as signals from Earth.

History of the Universe



10^{-32} seconds	1 microsecond	3 minutes	380,000 years	200 million years	400 million years	10 billion years	13.8 billion years
Inflation	**First Particles**	**First Nuclei**	**Dark Ages**	**First Stars**	**Galaxies and Dark Matter**	**Dark Energy**	**Today**
Initial expansion begins.	Neutrons, protons, and electrons form.	Hydrogen and helium ions form.	The first atoms form.	Gas and dust condense into stars.	Galaxies form in dark matter cradles.	Expansion accelerates.	Humans observe the universe.

SOURCE: NASA

↑ LuSEE-Night will listen for faint signals from the cosmic dark ages, a period that began about 380,000 years after the big bang, when neutral hydrogen atoms had begun to form, trapping the light of stars and galaxies.

with just some backyard equipment, you can easily detect neutral hydrogen in nearby galactic gas clouds close to that wavelength, which corresponds to a frequency of 1.42 gigahertz. But if the hydrogen signal originates from the dark ages, those 21 centimeters are lengthened to tens of meters. That means scientists need to listen to frequencies well below 50 megahertz—parts of the radio spectrum that are largely blocked by Earth's ionosphere.

Which is why the lunar far side holds such appeal. It may just be the quietest site in the inner solar system.

"It really is the only place in the solar system that never faces the Earth," says David DeBoer, a research astronomer at the University of California, Berkeley. "It really is kind of a wonderful, unique place."

For radio astronomy, things get even better during the lunar night, when the sun drops beneath the horizon and is blocked by the moon's mass. For up to 14 Earth days at a time, a spot on the moon's far side is about as electromagnetically dark as any place in the inner solar system can be. No radiation from the sun, no confounding signals from Earth. There may be signals from a few distant space probes, but otherwise, ideally, your antenna only hears the raw noise of the cosmos.

"When you get down to those very low radio frequencies, there's a source of noise that appears that's associated with the solar wind," says Caltech's Hallinan. Solar wind is the stream of charged particles that speed relentlessly from the sun. "And the only location where you can escape that within a billion kilometers of the Earth is on the lunar surface, on the nighttime side. The solar wind screams past it, and you get a cavity where you can hide away from that noise."

LuSEE-NIGHT'S RECEIVER looks simple, though there's really nothing simple about it. Up top are two dipole antennas, each of which consists of two collapsible rods pointing in opposite directions. The dipole antennas are mounted perpendicular to each other on a small turntable, forming an X when seen from above. Each dipole antenna extends to about 6 meters. The turntable sits atop a box of support equipment that's a bit less than a cubic meter in volume; the equipment bay, in turn, sits atop the Blue Ghost 2 lander, a boxy spacecraft about 2 meters tall.

"It's a beautiful instrument," says Stuart Bale, a physicist at the University of California, Berkeley, who is NASA's principal investigator for the project. "We don't even know what the radio sky looks like at these frequencies without the sun in the sky. I think that's what LuSEE-Night will give us."

The apparatus was designed to serve several incompatible needs: It had to be sensitive enough to detect very weak signals from deep space; rugged enough to withstand the extremes of the lunar environment; and quiet enough to not interfere with its own observations, yet loud enough to talk to Earth via relay satellite as needed. Plus the instrument had to stick to a budget of about US $40 million and not weigh more than 120 kilograms. The mission plan calls for two years of operations.

The antennas are made of a beryllium copper alloy, chosen for its high conductivity and stability as lunar temperatures plummet or soar by as much as 250 °C every time the sun rises or sets. LuSEE-Night will make precise voltage measurements of the signals it receives, using a high-impedance junction field-effect transistor to act as an amplifier for each antenna. The signals are then fed into a spectrometer—the main science instrument—which reads those voltages at 102.4 million samples per second. That high read rate is meant to prevent the exaggeration of any errors as faint signals are amplified. Scientists believe that a cosmic dark-ages signature would be five to six orders of magnitude weaker than the other signals that LuSEE-Night will record.

The turntable is there to help characterize the signals the antennas receive, so that, among other things, an ancient dark-ages signature can be distinguished from closer, newer signals from, say, galaxies or interstellar gas clouds. Data from the early universe should be virtually isotropic, meaning that it comes from all over the sky, regardless of the antennas' orientation. Newer signals are more likely to come from a specific direction. Hence the turntable: If you collect data over the course of a lunar

Illustrations by Chris Philpot

night, then reorient the antennas and listen again, you'll be better able to distinguish the distant from the very, very distant.

What's the ideal lunar landing spot if you want to take such readings? One as nearly opposite Earth as possible, on a flat plain. Not an easy thing to find on the moon's hummocky far side, but mission planners pored over maps made by lunar satellites and chose a prime location about 24 degrees south of the lunar equator.

Other lunar telescopes have been proposed for placement in the permanently shadowed craters near the moon's south pole, just over the horizon when viewed from Earth. Such craters are coveted for the water ice they may hold, and the low temperatures in them (below -240 °C) are great if you're doing infrared astronomy and need to keep your instruments cold. But the location is terrible if you're working in long-wavelength radio.

"Even the inside of such craters would be hard to shield from Earth-based radio frequency interference (RFI) signals," Leon Koopmans of the University of Groningen in the Netherlands, said in an email. "They refract off the crater rims and often, due to their long wavelength, simply penetrate right through the crater rim."

RFI is a major—and sometimes maddening—issue for sensitive instruments. The first-ever landing on the lunar far side was by the Chinese Chang'e 4 spacecraft, in 2019. It carried a low-frequency radio spectrometer, among other experiments. But it failed to return meaningful results, Chinese researchers said, mostly because of interference from the spacecraft itself.

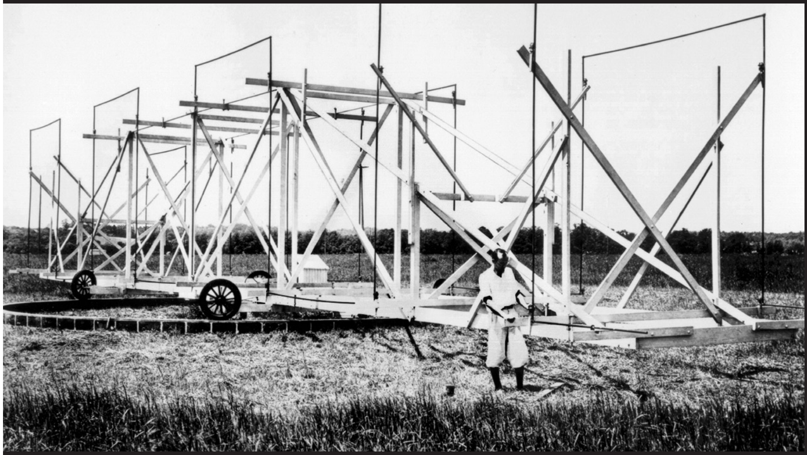
THE PLAN FOR Blue Ghost Mission 2 is to touch down soon after the sun has risen at the landing site. That will give mission managers two weeks to check out the spacecraft, take pictures, conduct other experiments that Blue Ghost carries, and charge LuSEE-Night's battery pack with its photovoltaic panels. Then, as local sunset comes, they'll turn everything off except for the LuSEE-Night receiver and a bare minimum of support systems.

There, in the frozen electromagnetic stillness, it will scan the spectrum between 0.1 and 50 MHz, gathering data for a low-frequency map of the sky—maybe including the first tantalizing signature of the dark ages.

"It's going to be really tough with that instrument," says Burns. "But we have some hardware and software techniques that... we're hoping will allow us to detect what's called the global or all-sky

CONTINUED ON P. 53

NRAO/AUI/NSF



The Accidental Birth of Radio Astronomy

Sometimes, a little interference makes history. Here, it's worth a pause to remember Karl Jansky, considered the father of radio astronomy. In 1928, he was a young engineer at Bell Telephone Laboratories in Holmdel, N.J., assigned to isolate sources of static in shortwave transatlantic telephone calls. Two years later, he built a 30-meter-long directional antenna [above], mostly out of brass and wood, and after accounting for thunderstorms and the like, there was still noise he couldn't explain. At first, its strength seemed to follow a daily cycle, rising and sinking with the sun. But after a few months' observation, the sun and the noise were badly out of sync.

It gradually became clear that the noise's period wasn't 24 hours; it was 23 hours and 56 minutes—the time it takes Earth to turn once relative to the stars. The strongest interference seemed to come from the direction of the constellation Sagittarius, which optical astronomy suggested was the center of the Milky Way. In 1933, Jansky published a paper in *Proceedings of the Institute of Radio Engineers* with a provocative title: "Electrical Disturbances Apparently of Extraterrestrial Origin." He had opened the electromagnetic spectrum up to astronomers, even though he never got to pursue radio astronomy himself. The interference he had defined was, to him, "star noise."

Thirty-two years later, two other Bell Labs scientists, Arno Penzias and Robert Wilson, ran into some interference of their own. In 1965, they were trying to adapt a horn antenna in Holmdel for radio astronomy—but there was a hiss, in the microwave band, coming from all parts of the sky. They had no idea what it was. They ruled out interference from New York City, not far to the north. They rewired the receiver. They cleaned out bird droppings in the antenna. Nothing worked.

Meanwhile, an hour's drive away, a team of physicists at Princeton University under Robert Dicke was trying to find proof of the big bang that began the universe 13.8 billion years ago. They theorized that it would have left a hiss, in the microwave band, coming from all parts of the sky. They'd begun to build an antenna. Then Dicke got a phone call from Penzias and Wilson, looking for help. "Well, boys, we've been scooped," he famously said when the call was over. Penzias and Wilson had accidentally found the cosmic microwave background, or CMB, the leftover radiation from the big bang.

Burns and his colleagues are figurative heirs to Jansky, Penzias, and Wilson. Researchers suggest that the giveaway signature of the cosmic dark ages may be a minuscule dip in the CMB. They theorize that dark-ages hydrogen may be detectable only because it has been absorbing a little bit of the microwave energy from the dawn of the universe. **—N.P.**

THE **QUEST** TO BUILD A TELESCOPE THAT CAN HEAR THE COSMIC DARK AGES

CONTINUED FROM P. 27

← "Just think. We're actually going to do cosmology from the moon," says Jack Burns. He and his colleagues already have early funding for LuSEE-Night's successor.

signal.... We, in principle, have the sensitivity." They'll listen and listen again over the course of the mission. That is, if their equipment doesn't freeze or fry first.

A major task for LuSEE-Night is to protect the electronics that run it. Temperature extremes are the biggest problem. Systems can be hardened against cosmic radiation, and a sturdy spacecraft should be able to handle the stresses of launch, flight, and landing. But how do you build it to last when temperatures range between 120 and −130 °C? With layers of insulation? Electric heaters to reduce nighttime chill?

"All of the above," says Burns. To reject daytime heat, there will be a multicell parabolic radiator panel on the outside of the equipment bay. To keep warm at night, there will be battery power—a lot of battery power. Of LuSEE-Night's launch mass of 108 kg, about 38 kg is a lithium-ion battery pack with a capacity of 7,160 watt-hours, mostly to generate heat. The battery cells will recharge photovoltaically after the sun rises. The all-important spectrometer has been programmed to cycle off periodically during the two weeks of darkness, so that the battery's state of charge doesn't drop below 8 percent; better to lose some observing time than lose the entire apparatus and not be able to revive it.

AND IF THEY CAN'T REVIVE IT? Burns has been through that before. In 2024 he watched helplessly as Odysseus, the first U.S.-made lunar lander in 50 years, touched down—and then went silent for 15 agonizing minutes until controllers in Texas realized they were receiving only occasional pings instead of detailed data. Odysseus had landed hard, snapped a leg, and ended up lying almost on its side.

As part of its scientific cargo, Odysseus carried ROLSES-1 (Radiowave Observations on the Lunar Surface of the photo-Electron Sheath), an experiment Burns and a friend had suggested to NASA years before. It was partly a test of technology, partly to study the complex interactions between sunlight, radiation, and lunar soil—there's enough electric charge in the soil sometimes that dust particles levitate above the moon's surface, which could potentially mess with radio observations. But Odysseus was damaged badly enough that instead of a week's worth of data, ROLSES got 2 hours, most of it recorded before the landing. A grad student working with Burns, Joshua Hibbard, managed to partially salvage the experiment and prove that ROLSES had worked: Hidden in its raw data were signals from Earth and the Milky Way.

"It was a harrowing experience," Burns said afterward, "and I've told my students and friends that I don't want to be first on a lander again. I want to be second, so that we have a greater chance to be successful." He says he feels good about LuSEE-Night being on the Blue Ghost 2 mission, especially after the successful Blue Ghost 1 landing. The ROLSES experiment, meanwhile, will get a second chance: ROLSES-2 has been scheduled to fly on Blue Ghost Mission 3, perhaps in 2028.

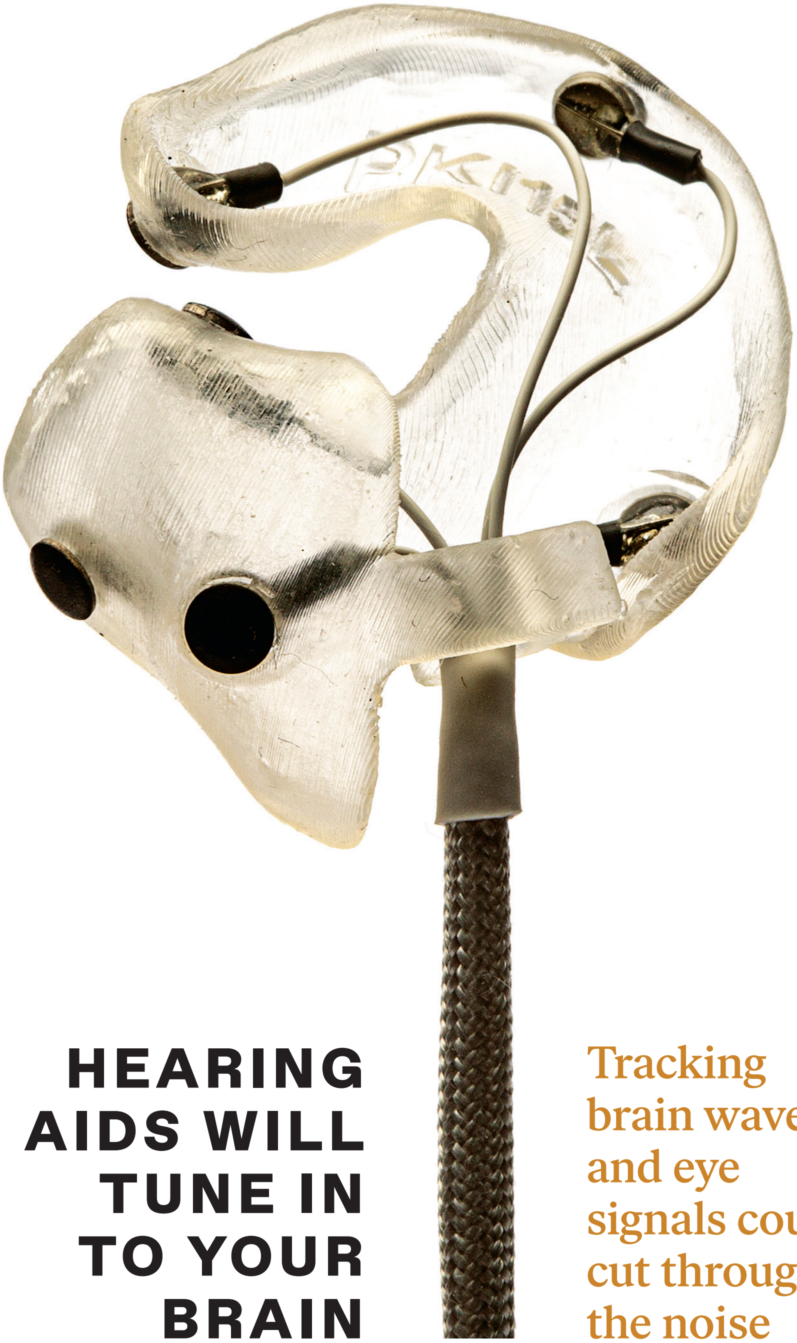
If LuSEE-Night succeeds, it will doubtless raise questions that require much more ambitious radio telescopes. Burns, Hallinan, and others have already gotten early NASA funding for a giant interferometric array on the moon called FarView. It would consist of a grid of 100,000 antenna nodes spread over 200 square kilometers, made of aluminum extracted from lunar soil. They say assembly could begin as soon as the 2030s, although political and budget realities may get in the way.

Through it all, Burns has gently pushed and prodded and lobbied, advocating for a lunar observatory through the terms of ten NASA administrators and seven U.S. presidents. He's probably learned more about Washington politics than he ever wanted. American presidents have a habit of reversing the space priorities of their predecessors, so missions have sometimes proceeded full force, then languished for years. With LuSEE-Night finally headed for launch, Burns at times sounds buoyant: "Just think. We're actually going to do cosmology from the moon." At other times, he's been blunt: "I never thought—none of us thought—that it would take 40 years."

"Like anything in science, there's no guarantee," says Burns. "But we need to look." ■

Photo by David Williams

These custom-molded hearing aids, created by Aarhus University's Center for Ear-EEG, use electrodes to measure tiny voltage changes on the surface of the skin inside the ear.



CENTER FOR EAR-EEG/ECE/AARHUS UNIVERSITY

HEARING AIDS WILL TUNE IN TO YOUR BRAIN

Tracking brain waves and eye signals could cut through the noise

By SHRUTHI RAGHAVENDRA

Imagine you’re at a bustling dinner party filled with laughter, music, and clinking silverware. You’re trying to follow a conversation across the table, but every word feels like it’s wrapped in noise. For most people, these types of party scenarios, where it’s difficult to filter out extraneous sounds and focus on a single source, are an occasional annoyance. For millions with hearing loss, they’re a daily challenge—and not just in busy settings.

Today’s hearing aids aren’t great at determining which sounds to amplify and which to ignore, and this often leaves users overwhelmed and fatigued. Even the routine act of conversing with a loved one during a car ride can be mentally draining, simply because the hum of the engine and road noises are magnified to create loud and constant background static that blurs speech.

In recent years, modern hearing aids have made impressive strides. They can, for example, use a technology called adaptive beamforming to focus their microphones in the direction of a talker. Noise-reduction settings also help decrease background cacophony, and some devices even use machine-learning-based analysis, trained on uploaded data, to detect certain environments—for example, a car or a party—and deploy custom settings.

That’s why I was initially surprised to find out that today’s state-of-the-art hearing aids aren’t good enough. “It’s like my ears work but my brain is tired,” I remember one elderly man complaining, frustrated with the inadequacy of his cutting-edge noise-suppression hearing aids. At the time, I was a graduate student at the University of Texas at Dallas, surveying individuals with hearing loss. The man’s insight led me to a realization: Mental strain is an unaddressed frontier of hearing technology.

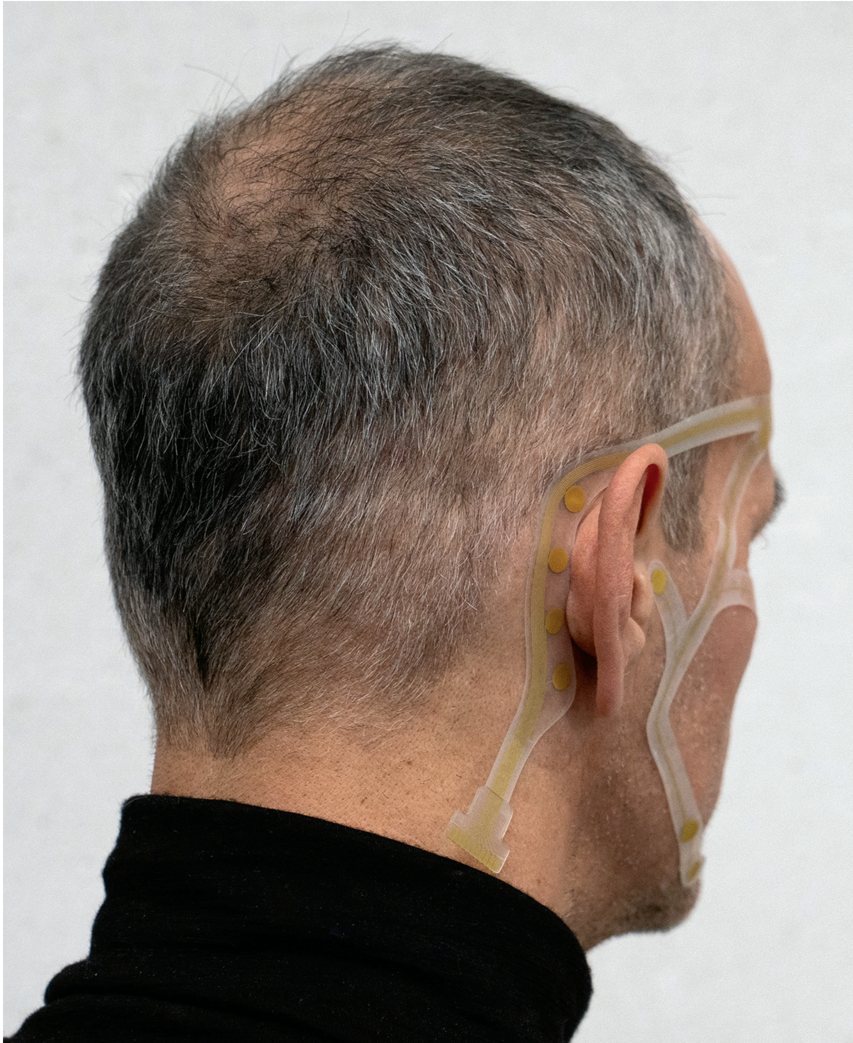
But what if hearing aids were more than just amplifiers? What if they were listeners too? I envision a new generation of intelligent hearing aids that not only boost sound but also read the wearer’s brain waves and other key physiological markers, enabling them to react accordingly to improve hearing and counter fatigue.

Until last spring, when I took time off to care for my child, I was a senior audio research scientist at Harman International, in Los Angeles. My work combined cognitive neuroscience, auditory prosthetics, and the processing of biosignals, which are measurable physiological cues that reflect our mental and physical state. I’m passionate about developing brain-computer interfaces (BCIs) and adaptive signal-processing systems that make life easier for people with hearing loss. And I’m not alone. A number of researchers and companies are working to create smart hearing aids, and it’s likely they’ll come on the market within a decade.

Two technologies in particular are poised to revolutionize hearing aids, offering personalized, fatigue-free listening experiences: electroencephalography (EEG), which tracks brain activity, and pupillometry, which uses eye measurements to gauge cognitive effort. These approaches might even be used to improve consumer audio devices, transforming the way we listen everywhere.

MORE THAN 430 MILLION people suffer from disabling hearing loss worldwide, including 34 million children, according to the World Health Organization. And the problem will likely get worse due to rising life expectancies and the fact that the world itself seems to be getting louder. By 2050, an estimated 2.5 billion people will suffer some degree of hearing loss and 700 million will require intervention. On top of that, as many as 1.4 billion of today’s young people—nearly half of

↓ Flex-printed electrode arrays, such as these from the Fraunhofer Institute for Digital Media Technology, offer a comfortable option for collecting high-quality EEG signals.



those aged 12 to 34—are at risk of permanent hearing loss from listening to audio devices too loud and for too long.

Every year, close to a trillion dollars is lost globally due to unaddressed hearing loss, a trend that is also likely getting more pronounced. That doesn't account for the significant emotional and physical toll on the hearing impaired, including isolation, loneliness, depression, shame, anxiety, sleep disturbances, and loss of balance.

And yet, despite widespread availability, hearing aid adoption remains low. According to a 2024 study published in *The Lancet*, only about 13 percent of American adults with hearing loss regularly wear hearing aids. Key reasons for this deficiency include discomfort, stigma, cost—and, crucially, frustration with the poor performance of hearing aids in noisy environments.

Historically, hearing technology has come a long way. As early as the 13th century, people began using horns of cows and rams as "ear trumpets." Commercial versions made of various materials, including brass and wood, came on the market in the early 19th century. (Beethoven, who famously began losing his hearing in his twenties, used variously shaped ear trumpets, some of which are now on display in a museum in Bonn, Germany.) But these contraptions were so bulky that users had to hold them with their hands or wear them within headbands. To avoid stigma, some even hid hearing aids inside furniture to mask their disability. In 1819, a special acoustic chair was designed for the king of Portugal, featuring arms ornately carved to look like open lion mouths, which helped transmit sound to the king's ear via speaking tubes.

Modern hearing aids came into being after the advent of electronics in the early 20th century. Early devices used vacuum tubes and then transistors to amplify sound, shrinking over time from bulky body-worn boxes to discreet units that fit behind or inside the ear. At their core, today's hearing aids still work on the same principle: A microphone picks up sound, a processor amplifies and shapes it to match the user's hearing loss, and a tiny speaker delivers the adjusted sound into the ear canal.

Today's best-in-class devices, like those from Oticon, Phonak, and Starkey, have pioneered increasingly advanced technologies, including the aforementioned beamforming microphones, frequency lowering to better pick up high-pitched sounds and voices, and machine learning to recognize and adapt to specific environments. For example, the device may reduce amplification in a quiet room to avoid escalating background hums or else increase amplification in a noisy café to make speech more intelligible.

Advances in the AI technique of deep learning, which relies on artificial neural networks to automatically recognize patterns, also hold enormous promise. Using context-aware algorithms, this technology can, for example, be used to help distinguish between speech and noise, predict and suppress unwanted clamor in real time, and attempt to clean up speech that is muffled or distorted.

The problem? As of right now, consumer systems respond only to external acoustic environments and not to the internal cognitive state of the listener—which means they act on imperfect and incomplete information. So, what if hearing aids were more empathetic? What if they could sense when the listener's brain feels tired or overwhelmed and automatically use that feedback to deploy advanced features?

WHEN IT COMES TO CREATING intelligent hearing aids, there are two main challenges. The first is building convenient, power-efficient wearable devices that accurately detect brain states. The second, perhaps more difficult step is decoding feedback from the brain and using that information to help hearing aids adapt in real time to the listener's cognitive state and auditory experience.

Let's start with EEG. This century-old noninvasive technology uses electrodes placed on the scalp to measure the brain's electrical activity through voltage fluctuations, which are recorded as "brain waves."

Clinically, EEG has long been applied for diagnosing epilepsy and sleep disorders, monitoring brain injuries, assessing hearing ability in infants and impaired individuals, and more. And while standard EEG requires conductive gel and bulky headsets, we now have versions that are far more portable and convenient. These breakthroughs have already allowed EEG to migrate from hospitals into the consumer tech spaces, driving everything from neurofeedback headbands to the BCIs in gaming and wellness apps that allow people to control devices with their minds.

The cEEGrid project at Oldenburg University, in Germany, positions lightweight adhesive electrodes around the ear to create a low-profile version. In Denmark, Aarhus University's Center for Ear-EEG also has an ear-based EEG system designed for comfort and portability. While the signal-to-noise ratio is slightly lower compared to head-worn EEG, these ear-based systems have proven sufficiently accurate for gauging attention, listening effort, hearing thresholds, and speech tracking in real time.

For hearing aids, EEG technology can pick up brain-wave patterns that reveal how well a listener is following speech: When listeners are paying attention, their brain rhythms synchronize with the syllabic rhythms of discourse, essentially tracking the speaker's cadence. By contrast, if the signal becomes weaker or less precise, it suggests the listener is struggling to comprehend and losing focus.

LEONA HOFMANN/FRAUNHOFER IDMT

↑ Brain-computer interfaces allow researchers to accurately determine a listener's focus in multitalker environments. Here, MIT Professor Christopher Smalt works on an attention-decoding system.

MIT LINCOLN LABORATORY

During my own Ph.D. research, I observed firsthand how real-time brain-wave patterns, picked up by EEG, can reflect the quality of a listener's speech cognition. For example, when participants successfully homed in on a single talker in a crowded room, their neural rhythms aligned nearly perfectly with that speaker's voice. It was as if there were a brain-based spotlight on that speaker! But when background fracas grew louder or the listener's attention drifted, those patterns waned, revealing stress in keeping up.

Today, researchers at Aarhus University, Oldenburg University, and MIT are developing attention-decoding algorithms specifically for auditory applications. For example, Oldenburg's cEEGrid technology has been used to successfully identify which of two speakers a listener is trying to hear. In a related study, researchers demonstrated that in-ear EEG can track the attended speech stream in multitalker environments.

All of this could prove transformational in creating neuroadaptive hearing aids. If a listener's EEG reveals a drop in speech tracking, the hearing aid could infer increased listening difficulty, even if ambient noise levels have remained constant. For example, if a hearing-impaired car driver can't focus on a conversation due to mental fatigue caused by background noise, the hearing aid could switch on beamforming to better augment the passenger's voice, as well as machine-learning settings to deploy sound canceling that blocks the din of the road.

Of course, there are several hurdles to cross before commercialization becomes possible. For one thing, EEG-paired hearing aids will need to handle the fact that neural responses differ from person to person, which means they will likely need to be calibrated individually to capture each user's unique brain-speech patterns.

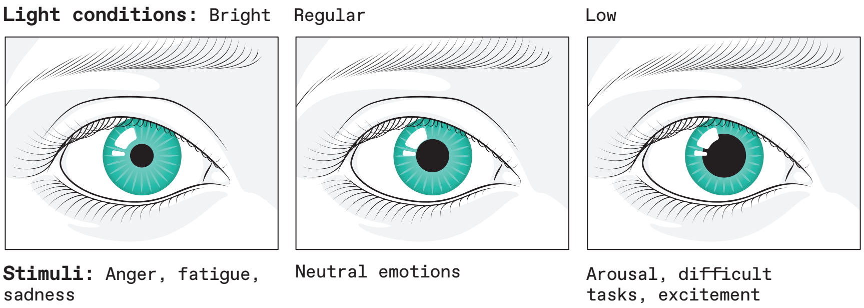
Additionally, EEG signals are themselves notoriously "noisy," especially in real-world environments. Luckily, we already have algorithms and processing tools for cleaning and organizing these signals so computer models can search for key patterns that predict mental states, including attention drift and fatigue.

Commercial versions of EEG-paired hearing aids will also need to be small and energy efficient when it comes to signal processing and real-time computation. And getting them to work reliably, despite head movement and daily activity, will be no small feat. Importantly, companies will need to resolve ethical and regulatory considerations, such as data ownership. To me, these challenges seem surmountable, especially with technology progressing at a rapid clip.

NOW LET'S CONSIDER a second way of reading brain states: through the listener's eyes.

When a person has trouble hearing and starts feeling overwhelmed, the body reacts. Heart-rate variability diminishes, indicating stress, and sweating increases. Researchers are investigating how these types of autonomic nervous-system responses can be measured and used to create smart hearing aids. For the purposes of this article, I will focus on a response that seems especially promising—namely, pupil size.

Pupillometry is the measurement of pupil size and how it changes in response to stimuli. We all know that pupils expand or contract depending


Light conditions: Bright
Regular
Low
Stimuli: Anger, fatigue, sadness
Neutral emotions
Arousal, difficult tasks, excitement

↑ Pupil size is determined by both external stimuli, such as light, and internal stimuli, such as fatigue or excitement.

on light brightness. As it turns out, pupil size is also an accurate means of evaluating attention, arousal, mental strain—and, crucially, listening effort.

In recent years, studies at University College London and Leiden University, in the Netherlands, have demonstrated that pupil dilation is consistently greater in hearing-impaired individuals when processing speech in noisy conditions. Research has also shown pupillometry to be a sensitive, objective correlate of speech intelligibility and mental strain. It could therefore offer a feedback mechanism for user-aware hearing aids that dynamically adjust amplification strategies, directional focus, or noise reduction based not just on the acoustic environment but on how hard the user is working to comprehend speech.

While more straightforward than EEG, pupillometry presents its own engineering challenges. Pupillometry requires a direct line of sight to the pupil, necessitating a stable, front-facing camera-to-eye configuration—which isn't easy to achieve when a wearer is moving around in real-world settings. On top of that, most pupil-tracking systems require infrared illumination and high-resolution optical cameras, which are too bulky and power intensive for the tiny housings of in-ear or behind-the-ear hearing aids. All this makes it unlikely that standalone hearing aids will include pupil-tracking hardware in the near future.

A more viable approach may be pairing hearing aids with smart glasses or other wearables that contain the necessary eye-tracking hardware. Products from companies like Tobii and Pupil Labs already offer real-time pupillometry via lightweight headgear for use in research, behavioral analysis, and assistive technology for people with medical conditions that limit movement but leave eye control intact. Apple's Vision Pro and other augmented reality or virtual reality platforms also include built-in eye-tracking sensors that could support pupillometry-driven adaptations for audio content.

Once pupil data is acquired, the next step will be real-time interpretation. Here, again, is where machine learning can use large datasets to detect patterns signifying increased cognitive load or attention shifts. For instance, if a listener's pupils dilate unnaturally during a conversation, signifying strain, the hearing aid could automatically engage a more aggressive noise suppression mode or narrow its directional microphone beam. These types of systems can also learn from contextual features, such as time of day or prior environments, to continuously refine their response strategies.

While no commercial hearing aid currently integrates pupillometry, adjacent industries are moving quickly. Emteq Labs is developing "emotion-sensing" glasses that combine facial and eye tracking, along with pupil measurement, to do things like evaluate mental health and capture consumer insights. Ethical controversies aside—just imagine what dystopian governments might do with emotion-reading eyewear!—such devices show that it's feasible to embed biosignal monitoring in consumer-grade smart glasses.

BACK AT THE DINNER party, it remains nearly impossible to participate in conversation. "Why even bother going out?" some ask. But that will soon change.

We're at the cusp of a paradigm shift in auditory technology, from device-centered to user-centered innovation. In the next five years, we may see hybrid solutions where EEG-enabled earbuds work in tandem with smart glasses. In 10 years, fully integrated biosignal-driven hearing aids could become the standard. And in 50? Perhaps audio systems will evolve into cognitive companions, devices that adjust, advise, and align with our mental state.

Personalizing hearing-assistance technology isn't just about improving clarity; it's also about easing mental fatigue, reducing social isolation, and empowering people to engage confidently with the world. Ultimately, it's about restoring dignity, connection, and joy. ■

→ Smart glasses that measure pupil size, such as these made by Tobii, could help determine listening strain.

TOP: CHRIS PHILPOT; BOTTOM: TOBII

THE LOW-COST ELECTRONICS UNCLOGGING THE U.K.'S GRID

New controllers unleash Scotland's wind power

BY PETER FAIRLEY

NATIONAL GRID ELECTRICITY TRANSMISSION/SMART WIRES

THE POWER SURGING through transmission lines over the iconic stone walls of England's northern countryside is pushing the United Kingdom's grid to its limits. To the north, Scottish wind farms have doubled their output over the past decade. In the south, where electricity demand is heaviest, electrification and new data centers promise to draw more power, but new generation is falling short. Construction on a new 3,280-megawatt nuclear power plant west of London lags years behind schedule.

The result is a lopsided flow of power that's maxing out transmission corridors from the Highlands to London. That grid strain won't ease anytime soon. New lines linking Scotland to southern England are at least three to four years from operation, and at risk of further delays from fierce local opposition.

At the same time, U.K. Prime Minister Keir Starmer is bent on installing even more wind power and slashing fossil-fuel generation by 2030. His Labour government says low-carbon power is cheaper and more secure than natural gas, much of which comes from Norway via the world's longest underwater gas pipeline and is vulnerable to disruption and sabotage.

The U.K.'s resulting grid congestion prevents transmission operators from delivering some of their cleanest, cheapest generation to all of the consumers who want it. Congestion is a perennial problem whenever power consumption is on the rise. It pushes circuits to their thermal limits and creates grid stability or security constraints.

With congestion relief needed now, the U.K.'s grid operators are getting creative, rapidly tapping new cable designs and innovations in power electronics to squeeze more power through existing transmission corridors. These grid-enhancing technologies, or GETs, present a low-cost way to bridge the gap until new lines can be built.

"GETs allow us to operate the system harder before an investment arrives, and they save a s***load of money," says Julian Leslie, chief engineer and director of strategic energy planning at the National Energy System Operator (NESO), the Warwick-based agency that directs U.K. energy markets and infrastructure.

The U.K.'s extreme grid challenge has made it ground zero for some of the boldest GETs testing and deployment.

The SmartValve array at Penwortham substation near Preston, England, is one of several new grid-enhancing technologies aimed at moving more power throughout the U.K.

Such innovation involves some risk, because an intervention anywhere on the U.K.'s tightly meshed power system can have system-wide impacts. (Grid operators elsewhere are choosing to start with GETs at their systems' periphery—where there's less impact if something goes wrong.)

The question is how far—and how fast—the U.K.'s grid operators can push GETs capabilities. The new technologies still have a limited track record, so operators are cautiously feeling their way toward heavier investment. Power system experts also have unanswered questions about these advanced grid capabilities. For example, will they create more complexity than grid operators can manage in real time? Might feedback between different devices destabilize the grid?

There is no consensus yet as to how to even screen for such risks, let alone protect against them, says Robin Preece, professor in future power systems at the University of Manchester, in England. "We're at the start of establishing that now, but we're building at the same time. So it's kind of this race between the necessity to get this technology installed as quickly as possible, and our ability to fully understand what›s happening."

ONE OF THE MOST innovative and high-stakes tricks in the U.K.'s toolbox employs electronic power-flow controllers, devices that shift electricity from jammed circuits to those with spare capacity. These devices have been able to finesse enough additional wind power through grid bottlenecks to replace an entire gas-fired generator. Installed in northern England four years ago by Smart Wires, based in Durham, N.C., these SmartValves are expected to help even more as NESO installs more of them and masters their capabilities.

Warwick-based National Grid Electricity Transmission, the grid operator for England and Wales, is adding SmartValves and also replacing several thousand kilometers of overhead wire with advanced conductors that can carry more current. And it's using a technique called dynamic line rating, whereby sensors and models work together to predict when weather conditions will allow lines to carry extra current.

Other kinds of GETs are also being used globally. Advanced conductors are the most widely deployed. Dynamic line rating is increasingly common in European countries, and U.S. utilities are beginning to take it seriously. Europe also leads the world in topology-optimization software, which reconfigures power routes to alleviate congestion, and advanced power-flow control devices like SmartValves.

SmartValves' chops stand out at the Penwortham substation in Lancashire, England, one of two National Grid sites where the device made its U.K. debut in 2021. Penwortham substation is a major transmission hub, whose spokes desperately need congestion relief. Auditory evidence of heavy power flows was clear during my visit to the substation, which buzzes loudly. The sound is due to the electromechanical stresses on the substation's massive transformers, explains my guide, National Grid commissioned engineer Paul Lloyd.

Penwortham's transformers, circuits, and protective relays are spread over 15 hectares, sandwiched between pastureland and suburban homes near Preston, a small city north of Manchester. Power arrives from the north on two pairs of 400-kilovolt AC lines, and most of it exits southward via 400-kV and 275-kV double-circuit wires.

What makes the substation a strategic test bed for GETs is its position just north of the U.K. grid's biggest bottleneck, known as Boundary B7a, which runs east to west across the island. Nine circuits traverse the B7a: the four AC lines headed south from Penwortham, four AC lines closer to Yorkshire's North Sea coast, and a high-voltage direct-current (HVDC) link offshore. In theory, those circuits can collectively carry 13.6 gigawatts across the B7a. But NESO caps its flow at several gigawatts lower to ensure that no circuits overload if any two lines turn off.

Such limits are necessary for grid reliability, but they are leaving terawatt-hours of wind power stranded in Scotland and increasing consumers' energy costs: an extra £196 million (US $265 million) in 2024 alone. The costs stem from NESO

Scottish wind farms have doubled their power output over the past decade, but it often gets stranded due to grid congestion in England [above]. Transmission lines [right] running across England's countryside are maxed out, creating bottlenecks in the grid that prevent some carbon-free power from reaching customers.

ANDREAS BERTHOLD/ALAMY; VINCENT LOWE/ALAMY

Engineers install dynamic line rating technology from the Boston-based company LineVision on National Grid’s transmission network.

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having to ramp up gas-fired generators to meet demand down south while simultaneously compensating wind-farm operators for curtailing their output, as required under U.K. policy.

So National Grid keeps tweaking Penwortham. In 2011 the substation got its first big GET: phase-shifting transformers (PSTs), a type of analog flow controller. PSTs adjust power flow by creating an AC waveform whose alternating voltage leads or lags its alternating current. They do so by each PST using a pair of connected transformers to selectively combine power from an AC transmission circuit’s three phases. Motors reposition electrical connections on the transformer coils to adjust flows.

Penwortham’s pair of 540-tonne PSTs occupy the entire south end of the substation, along with their dedicated chillers, relays, and power supplies. Delivering all that hardware required extensive road closures and floating a huge barge up the adjacent River Ribble, an event that made national news.

The SmartValves at Penwortham stand in stark contrast to the PSTs’ heft, complexity, and mechanics. SmartValves are a type of static synchronous series compensator, or SSSC—a solid-state alternative to PSTs that employs power electronics to tweak power flows in milliseconds. I saw two sets of them tucked into a corner of the substation, occupying a quarter of the area of the PSTs.

The SmartValves are first and foremost an insurance policy to guard against a potentially crippling event: the sudden loss of one of the B7a’s 400-kV lines. If that were to happen, gigawatts of power would instantly seek another route over neighboring lines. And if it happened on a windy day, when lots of power is streaming in from the north, the resulting surge could overload the 275-kV circuits headed from Penwortham to Liverpool. The SmartValves’ job is to save the day.

They do this by adding impedance to the 275-kV lines, thus acting to divert more power to the remaining 400-kV lines. This rerouting of power prevents a blackout that could potentially cascade through the grid. The upside to that protection is that NESO can safely schedule an additional 350 MW over the B7a.

The savings add up. “That’s 350 MW of wind you’re no longer curtailing from wind farms. So that’s 350 times £100 a megawatt-hour,” says Leslie, at NESO. “That’s also 350 MW of gas-fired power that you don’t need to replace the wind. So that’s 350 times £120 a megawatt-hour. The numbers get big quickly.”

Mark Osborne, the National Grid lead asset life-cycle engineer managing its SmartValve projects, estimates the devices are saving U.K. customers over £100 million (US $132 million) a year. At that rate, they’ll pay for themselves “within a few years,” Osborne says. By utility standards, where investments are normally amortized over decades, that’s “almost immediately,” he adds.

THE WAY SMART WIRES’ SSSC devices adjust power flow is based on emulating impedance, which is a strange beast created by AC power. An AC flow’s changing magnetic field induces an additional voltage in the line’s conductor, which then acts as a drag on the initial field. Smart Wires’ SSSC devices alter power flow by emulating that natural process, effectively adding or subtracting impedance by adding their own voltage wave to the line. Adding a wave that leads the original voltage wave will boost flow, while adding a lagging wave will reduce flow.

The SSSC’s submodules of capacitors and high-speed insulated-gate bipolar transistors operate in sequence to absorb power from a line and synthesize its novel impedance-altering waves. And thanks to its digital controls and switches, the device can within milliseconds flip from maximum power push to maximum pull.

You can trace the development of SSSCs to the advent of HVDC transmission in the 1950s. HVDC converters take power from an AC grid and efficiently convert it and transfer it over a DC line to another point in the same grid, or to a neighboring AC grid. In 1985, Narain Hingorani, an HVDC expert at the Palo Alto–based Electric Power Research Institute, showed that similar converters could modulate the flow of an AC line. Four years later, Westinghouse engineer Laszlo Gyugyi proposed SSSCs, which became the basis for Smart Wires' boxes.

Major power-equipment manufacturers tried to commercialize SSSCs in the early 2000s. But utilities had little need for flow control back then because they had plenty of conventional power plants that could meet local demand when transmission lines were full.

The picture changed as solar and wind generation exploded and conventional plants began shutting down. In years past, grid operators addressed grid congestion by turning power plants on or off in strategic locations. But as of 2024, the U.K. had shut down all of its coal-fired power plants—save one, which now burns wood—and it has vowed to slash gas-fired generation from about a quarter of electricity supply in 2024 to at most 5 percent in 2030.

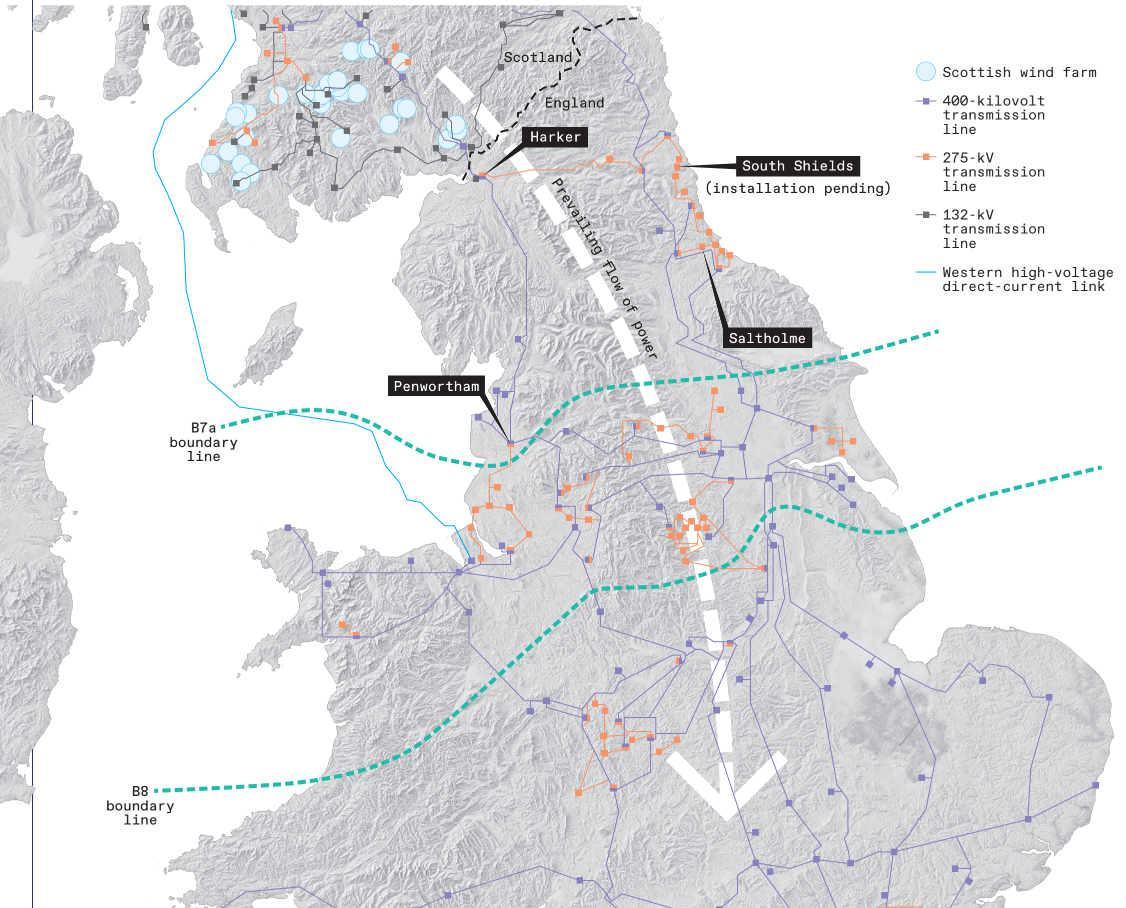
To seize the emerging market opportunity presented by changing grid operations, Smart Wires had to make a crucial technology upgrade: ditching transformers. The company's first SSSC, and those from other suppliers, relied on a transformer to absorb lightning, voltage surges, and every other grid assault that could fry their power electronics. This made them bulky and added cost. So Smart Wires engineers set to work in 2017 to see if they could live without the transformer, says Frank Kreikebaum, Smart Wires's interim chief of engineering. Two years later the company had assembled a transformerless electronic shield. It consisted of a suite of filters and diverters, along with a control system to activate them. Ditching the transformer produced a trim, standardized product—a modular system-in-a-box.

SmartValves work at any voltage and are generally ganged together to achieve a desired level of flow control. They can be delivered fast, and they fit in the kinds of tight spaces that are common in substations. "It's not about cost, even though we're competitive there. It's about 'how quick' and 'can it fit,'" says Kreikebaum.

And if the grid's pinch point shifts? The devices can be quickly moved to another substation. "It's a Lego-brick build," says Owen Wilkes, National Grid's director of network design. Wilkes's team decides where to add equipment based on today's best projections, but he appreciates the flexibility to respond to unexpected changes.

National Grid's deployments in 2021 were the highest-voltage installation of SSSCs at the time, and success there is fueling expansion. National Grid now has packs of SmartValves installed at three substations in northern England and under construction at another, with five more installations planned in that area. Smart Wires has also commissioned commercial projects at transmission substations in Australia, Brazil, Colombia, and the United States.

IN ADDITION TO SSSCS, National Grid has deployed lidar that senses sag on Penwortham's 275-kV lines—an indication that they're starting to overheat. The sensors are part of a dynamic line rating system and help grid operators maximize the amount of current that high-voltage lines can carry based on near-real-time weather conditions. (Cooler weather means more



The lack of transmission lines available to move power flowing south from Scottish wind farms has caused grid congestion in England. To better manage it, the U.K. has installed SmartValves at three substations in northern England—Penwortham, Harker, and Saltholme—and is constructing a fourth at South Shields.

Phase-shifting transformers (PSTs) were installed in 2012 at the Penwortham substation and are the analog predecessor to SmartValves. They're powerful but also bulky and relatively inflexible. It can take 10 minutes or more for the PST's motorized actuators at Penwortham to tap their full range of flow control, whereas SmartValves can shift within milliseconds.

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capacity.) Now the same technology is being deployed across the B7a—a £1 million investment that is projected to save consumers £33 million annually, says Corin Ireland, a National Grid optimization engineer with the task of seizing GETs opportunities.

There are also a lot of old conductor wires being swapped out for those that can carry more power. National Grid's business plan calls for 2,416 kilometers of such reconductoring over the coming five years, which is about 20 percent of its system. Scotland's transmission operators are busy with their own big swaps.

But while National Grid and NESO are making some of the boldest deployments of GETs in the world, they're not fully tapping the technologies' capabilities. That's partly due to the conservative nature of power utilities, and partly because grid operators already have plenty to keep their eyes on. It also stems from the unknowns that still surround GETs, like whether they might take the grid in unforeseen directions if allowed to respond automatically, or get stuck in a feedback loop responding to each other. Imagine SmartValve controllers at different substations fighting, with one substation jumping to remove impedance that the other just added, causing fluctuating power flows.

"These technologies operate very quickly, but the computers in the control room are still very reliant on people making decisions," says Ireland. "So there are time scales that we have to take into consideration when planning and operating the network."

This kind of conservative dispatching leaves value on the table. For example, the dynamic line rating models can spit out new line ratings every 15 minutes, but grid operators get updates only every 24 hours. Fewer updates means fewer opportunities to tap the system's ability to boost capacity. Similarly, for SmartValves, NESO activates installations at only one substation at a time. And control-room operators turn them on manually, even though the devices could automatically respond to faults within milliseconds.

Modeling by Smart Wires and National Grid shows a significant capacity boost across Boundary B7a if Penwortham's SmartValves were to work in tandem with another set further up the line. For example, when Penwortham is adding impedance to push megawatts off the 275-kV lines, a set closer to Scotland could simultaneously pull the power north, nudging the sum over to the B7a's eastern circuits. Simulations by Andy Hiorns, a former National Grid planning director who consults for Smart Wires, suggest that this kind of cooperative action should increase the B7a circuits' usable capacity by another 250 to 300 MW. "You double the effectiveness by using them as pairs," he says.

Operating multiple flow controllers may become necessary for unlocking the next boundary en route to London, south of the B7a, called Boundary B8. As dynamic line rating, beefier conductors, and SmartValves send more power across the B7a, lines traversing B8 are reaching their limits. Eventually, every boundary along the route will have to be upgraded.

Meanwhile, back at its U.S. headquarters, Smart Wires is developing other applications for its SSSCs, such as filtering out power oscillations that can destabilize grids and reduce allowable transfers. That capability could be unlocked remotely with firmware.

The company is also working on a test program that could turn on pairs of SmartValve installations during slack moments when there isn't much going on in the control rooms. That would give National Grid and NESO operators an opportunity to observe the impacts, and to get more comfortable with the technology.

National Grid and Smart Wires are also hard at work developing industry-first optimization software for coordinating flow-control devices. "It's possible to extend the technology from how we're using it today," says Ireland at National Grid. "That's the exciting bit."

NESO's Julian Leslie shares that excitement and says he expects SmartValves to begin working together to ease power through the grid—once the operators have the modeling right and get a little more comfortable with the technology. "It's a great innovation that has the potential to be really transformational," he says. "We're just not quite there yet." ■

Map by Chris Philpot

EXPRESSION HAS NO LIMIT*
NEW EXHIBITION
ART
CONTEMPORARY
BEEPLE
SMILE
LZ Tower
NEXT LANDMARK
LZ Tower
CITY TRANSIT
RIO BRANCO
FUTURE
TAXI
RTHBOUND LINE ARRI

By **GABRIEL RENÉ** & **CAPM PETERSEN**

THE SPATIAL WEB WILL INTEGRATE AI AGENTS, ROBOTS, AND EVERYTHING ELSE

A new standard seeks to push the World Wide Web into physical space

HOLO ART MUSEUM
SOUTHBOUND LINE 2 ARRIVING IN

PHOTO CREDIT: FIRST LASTNAME

WITHIN YEARS of its 1991 release, the World Wide Web connected an internet that was overrun with many thousands of individual, fragmented digital documents. HyperText Markup Language (HTML) represented a daring leap. It combined the age-old idea of hypertext with the internet's global reach. Tim Berners-Lee's new language offered up a lingua franca for interconnected information.

Today, following the social media revolution, a new phase of the internet is emerging. The Spatial Web promises to connect a physical world full of devices, phones, wearables, robots, drones, and even AI agents. In May 2025, the IEEE Standards Association approved a set of standards (IEEE 2874–2025) that defines the Spatial Web.

The Spatial Web is essentially three coordinated systems. One layer, the Hyperspace Modeling Language (HSML), describes places, things, events, and activities in a universal language. One layer, the Hyperspace Transaction Protocol (HSTP), verifies every transaction to ensure every agent and object in the system is what it claims to be and is allowed to do what it's asking. And one layer, the Universal Domain Graph (UDG), maintains a continuously updated map of all things and their relationships.

All three layers working together enable your car, your home, your city's traffic system, and emergency responders to understand each other and coordinate automatically. They're all speaking the same language, following the same trust rules, and referencing the same real-time map of what's happening.

But that "real-time map" has real limitations. Unlike the document-centered web, the Spatial Web tracks a shared, authoritative model of physical reality. And that model is dynamic and responsive to real-world changes, too. Severe weather events happen. Energy prices fluctuate. Inventory is updated. Regulations change. Because all agents and objects reference the same continuously updated digital representation of the physical world, they can respond to changes as they occur. A thermostat and battery system won't just understand each other—they will be able to negotiate new strategies as conditions change. A drone won't just know the no-fly zones when it takes off; it will keep tabs on them in flight, and can adjust its route if restrictions change. A produce buyer won't query yesterday's harvest; they'll query today's ripeness and inventory. The Spatial Web adapts because everything is reading from and writing to the same dynamic map of the world.

PROTOCOL	PURPOSE
HSML (Hyperspace Modeling Language)	Describes what a Spatial Web entity is and what it does
HSTP (Hyperspace Transaction Protocol)	Governs how Spatial Web entities negotiate and enforce system policies
UDG (Universal Domain Graph)	Catalogs and links registered entities, activities, and permissions

THE EMERGING Spatial Web will rely on standards that are analogous to the World Wide Web's protocols. HSML describes entities much like the web describes documents; HSTP governs interactions similar to how the web governs access to documents; and UDG maps relationships in a way that mirrors how the web locates resources.

The Spatial Web also embeds trust and accountability into its foundations through credentials, rights, permissions, and policies that are machine readable and verifiable. Using decentralized identifiers and cryptographic signing, every entity can verify the identity and permissions of others without a central authority. Every transaction is verifiable and auditable. This means an ambulance can securely request green lights from traffic systems; smart cities can coordinate energy distribution across neighborhoods; supply-chain systems can track produce from orchard to buyer with full transparency. Security and privacy are not merely concerns that are layered on top. They're built into the protocol layer itself.

We'll come to some of the practicalities of the Spatial Web a little later—for instance, where these various files might be stored, and how each entity can stay up-to-date with everything else in its network. But for now, let's first consider a few specific ways devices and AI agents can use the Spatial Web—via HSML, HSTP, and UDG standards—to more seamlessly interact with people, objects, and physical spaces.

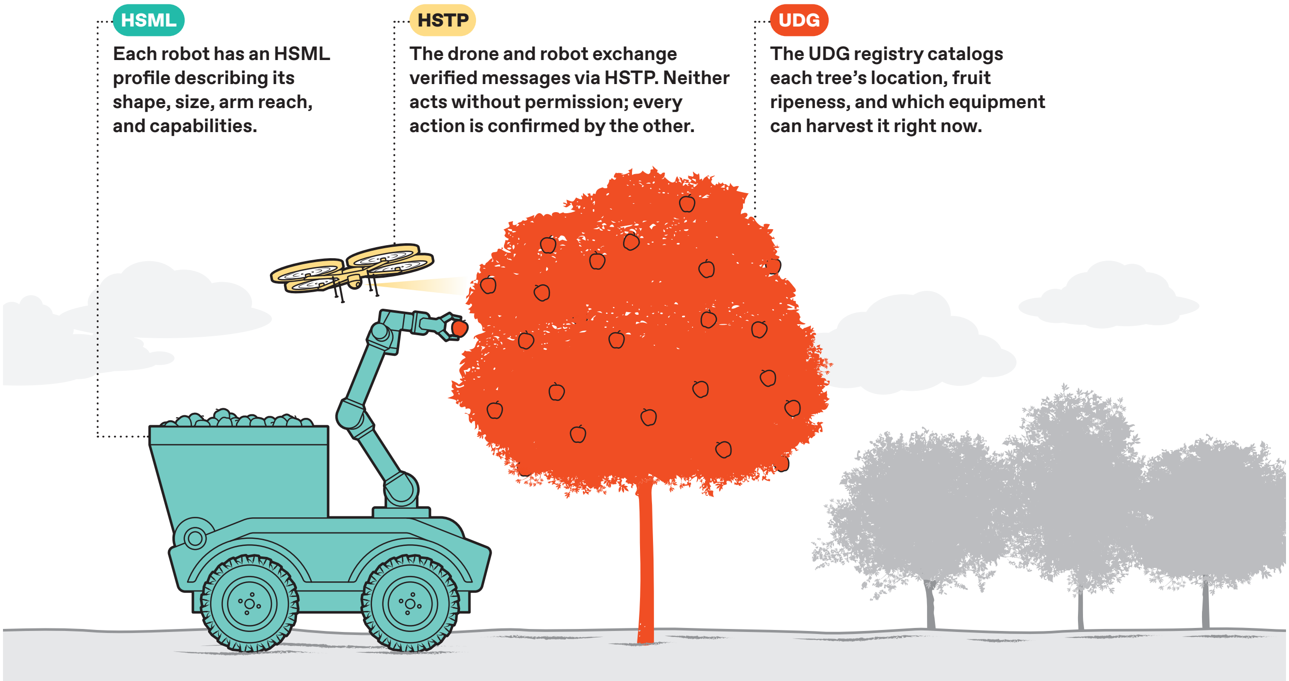
VERSES, the New Westminster, B.C., Canada–based AI company where we work, recently collaborated with researchers at University College London on EcoNet, a test home where two AI agents—one controlling a thermostat, the other a wall-mounted energy-storage battery system—collaborated to keep the space comfortable while saving money and cutting emissions.

Every 10 minutes, the AI agents evaluated competing strategies to balance comfort, cost, and carbon footprint. The EcoNet system used HSML to describe a set of competing goals. One goal involved keeping the living room between 22 and 25 °C. A second goal involved avoiding discharging the house's energy storage during peak hours.

The Spatial Web's shared digital network protocol, the UDG, helped the smart devices work together in real time. Then, its secure communication method (via the HSTP standard) enabled decisions that followed the system's rules and commands. The system cut both energy costs and carbon emissions by 15 to 20 percent. Verses demonstrated EcoNet in March at the 2025 AI UK exhibition at the Alan Turing Institute, in London.

At scale, an EcoNet-like architecture might enable entire neighborhoods to act a little like intelligent organisms, optimizing collective energy use and accelerating the shift to a more resilient, renewable grid.

PREVIOUS PAGES: VERSES


HSML
Each robot has an HSML profile describing its shape, size, arm reach, and capabilities.
HSTP
The drone and robot exchange verified messages via HSTP. Neither acts without permission; every action is confirmed by the other.
UDG
The UDG registry catalogs each tree's location, fruit ripeness, and which equipment can harvest it right now.

Ripeness Tracking Ends Guesswork in the Digital Orchard

PICKING APPLES is about precision timing. Get it right and the apple arrives at the grocery store ready to be eaten; get it wrong and the fruit rots or tastes bad. Using the Spatial Web, robots and drones can cut down the guesswork, keeping tabs on each tree's readiness for picking and then directing apple-picking bots when and where to pick.

WHEN AN AMBULANCE rushes to an emergency, the ambulance driver still depends on surrounding traffic to react to the siren. But autonomous vehicles may not know which direction the ambulance is coming from or how to properly respond to the ambulance in time, because autonomous vehicles operate without shared context.

The Spatial Web can address this shortcoming via HSML. A shared HSML document describes the state and relationships of things in a given neighborhood or at a given intersection. Properties being recorded in the HSML document might include the color, location, and behavior of a given traffic light.

With this shared context, an ambulance can issue a Spatial Web query like "Find all autonomous vehicles and traffic infrastructure within 200 meters of my route." Using the HSTP, it can request green lights, reroute cars, and alert pedestrians through connected devices.

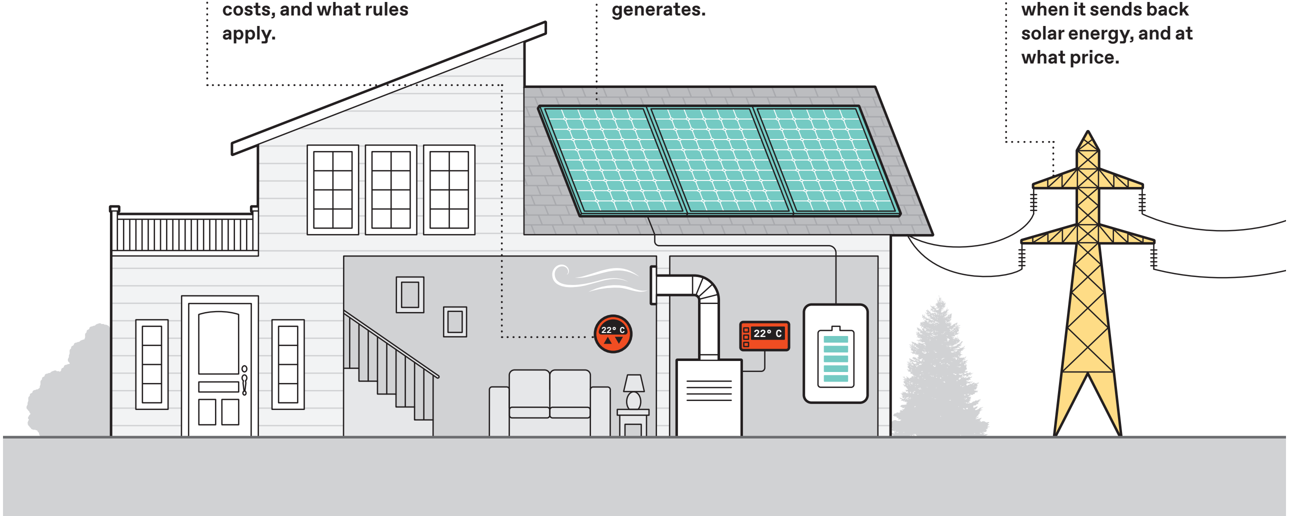
ALTITUDE LIMITS, flight windows, and no-fly zones for drones today are difficult to enforce consistently. While drone makers offer firmware and geofencing database updates, there is no universal standard ensuring that all drones will access the same, verified, real-time data. Many drones operate with outdated information about restricted areas and are today oblivious to emergency or temporary restrictions, unless that drone's user actively intervenes to make necessary updates and changes to its firmware and operating parameters.

The Spatial Web provides drones with the necessary context to navigate responsibly. Regulators can use HSML to define constraints like "no flights above 120 meters after sunset and within 500 meters of a hospital." Those constraints would then be published to the UDG, where drones operating within the relevant air space can apply these constraints in real time.

Before takeoff, a drone might issue a Spatial Web query such as "What restrictions apply to my delivery route?" HSTP allows the drone to confirm its air-space authorization, share its intended path, and adjust midflight if conditions or regulations change.

The same Spatial Web infrastructure can also be used in emergencies. After a natural disaster, drones could be temporarily authorized to enter restricted zones to assist with search and rescue or deliver supplies—all within a secure, trackable framework.

Illustration by Chris Philpot



UDG

The thermostat checks its UDG resources to monitor how much energy is available, what it costs, and what rules apply.

HSML

The panel broadcasts its HSML profile—its location, current sunlight, and how much power it generates.

HSTP

The home negotiates with the power grid via HSTP—allowing it to coordinate when it draws power, when it sends back solar energy, and at what price.

Smart Homes Coordinate Resources and Negotiate With the Grid

MOST HOMES treat heating, cooling, and electricity as separate problems solved by separate appliances. But what if your thermostat, solar panels, and home battery could talk to each other and to the power company in real time? Working together via Spatial Web standards, smart home devices could together cut your energy bill by automatically buying and selling power at the best price while still keeping you comfortable.

COORDINATING AUTONOMOUS systems in the air is hard. On the moon, it's harder still. NASA's Jet Propulsion Laboratory (JPL) in Pasadena, Calif., frequently collaborates with multiple agencies, universities, and contractors, each using different simulation systems and proprietary platforms. Testing how multiple organizations and lunar rovers will one day cooperate on the moon requires a shared language and a common model of the rovers and environment. The Spatial Web makes this possible.

In one demo, rover teams from JPL and California State University, Northridge, each operated their own digital-twin and simulation environments using HSML to coordinate a simulated lunar rescue involving lunar rovers. When one virtual rover got stuck in a crater, HSML allowed the stuck rover to send out real-time geometry, sensor observations, and activity data. The virtual rovers also shared internal models from different physics modeling engines, including parameters like position, velocity, acceleration, and mass. The rover simulation, in other words, demonstrated how HSML-powered digital twins can assist in autonomous collaboration over challenging environments—even on the (virtual) moon.

ROUGHLY ONE-THIRD of all food produced around the world spoils before it ever reaches a plate, driving up emissions, reducing profits, and contributing to global hunger.

However, using Spatial Web standards, for instance, a peach orchard could use HSML to describe the ripeness, temperature, and shelf life of each crate. These descriptions are published to the local UDG, where retailers can query live inventory across regions. Using the Spatial Web, a buyer might query their local network, "What peaches are ready to harvest within 500 kilometers and meet my freshness criteria?"

HSTP can simplify the negotiation, delivery, and policy verification of such a query. If a buyer rejects a shipment, the grower can redirect it to a new buyer, such as a juicer or a nearby store, before the fruit goes to waste.

Instead of rigid logistics and guesswork, Spatial Web supply chains have the potential to become more adaptive, intelligent, and responsive to both external demand and internal conditions. The result will be less spoilage, better margins, faster payments, and fresher food.

Illustrations by Chris Philpot

THE SPATIAL WEB standard is still in an early phase. HTML was published in 1991, but the first browser didn't arrive until 1993. Additional web standards on top of that, like cascading style sheets, didn't come in until 1996. The Spatial Web, ratified last year, is similarly rolling out in stages. Ultimately the foundation we are laying in place paves the way for a Spatial Web that spans not so much pages and data files but rather people, places, and things.

Standards succeed only when they disappear into the background. No one thinks about TCP/IP standards when reading email, although email relies on these standards in every message that is sent or received. Similarly, no layperson will need to understand how standards like HSML, HSTP, or UDG work. All these components of the Spatial Web will, like other protocols and standards before it, simply do the hard communication and computation work behind the scenes. Where, then, do HSML, HSTP, and UDG assets ultimately reside? Do they all sit on some cloud server somewhere? Or perhaps these various digital files are all scattered across individual devices and Internet of Things nodes?

Unfortunately, there is no single answer to these pertinent questions. On the other hand, the World Wide Web didn't launch fully formed either. Its earliest days often tested trial implementations of new standards and technologies, because nothing like the truly widespread, instantaneous, global scale of the web had ever been rolled out before.

For the Spatial Web, simple agents like IoT devices, for instance, could host HSML files and other Spatial Web assets on-device. In more complex settings, like smart cities or industrial systems, cloud servers or shared storage systems would provide a more remote and cloud-based kind of HSTP, HSML, and UDG deployment.

But no matter how the Spatial Web is implemented, whether fully remote or fully localized, cybersecurity will remain an essential priority.

Because the Spatial Web coordinates actions across a vast many objects and agents making real-time decisions, a single compromised device or rogue agent could cascade failures across entire systems. Spatial Web standards prevent this by encoding identity, permissions, and cryptographic verification directly into every entity and transaction—so that each agent (depending on its permissions) can authenticate others without relying on a vulnerable central authority.

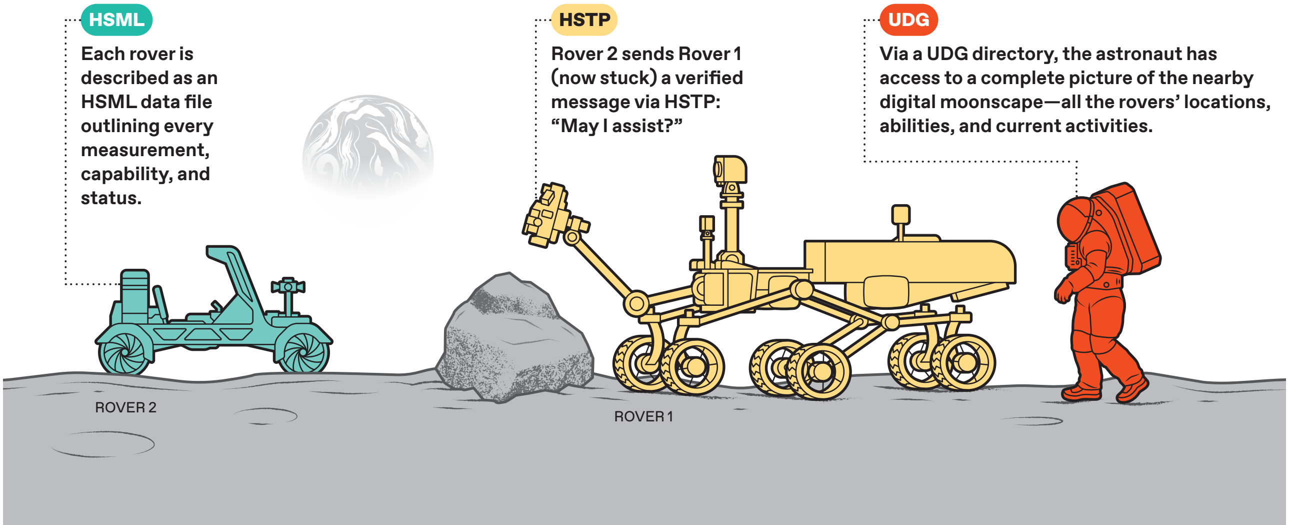
Which is why HSML, HSTP, and UDG standards embed identity, access, and policy enforcement, via decentralized identifiers. Furthermore, the HSTP standard ensures that every transaction is cryptographically confirmed as coming from an authorized agent and recorded in a permanent, tamper-proof history that cannot be altered after the fact.

Ultimately, too, another aspect of any Spatial Web deployment will be the registries that must scale up to manage billions of entities and agents. That is a larger, later-stage question to be tackled, no doubt, in future implementations of the Spatial Web. Nevertheless, even in the Spatial Web's earliest incarnations today, we have already abstracted these complex concerns behind a secure, standards-based interface.

The standards that defined the World Wide Web connected information. The Spatial Web will begin to interconnect the physical world and the many devices and AI agents operating in it. And with the new Spatial Web standards—and trial runs in homes, streets, skies, and on the (virtual) moon—an increasingly interconnected Spatial Web future is no longer theoretical. A standardized Spatial Web is today as actual, and as achievable, as HTML. ■

Lunar Rovers Collaborate on Shared Moon Missions

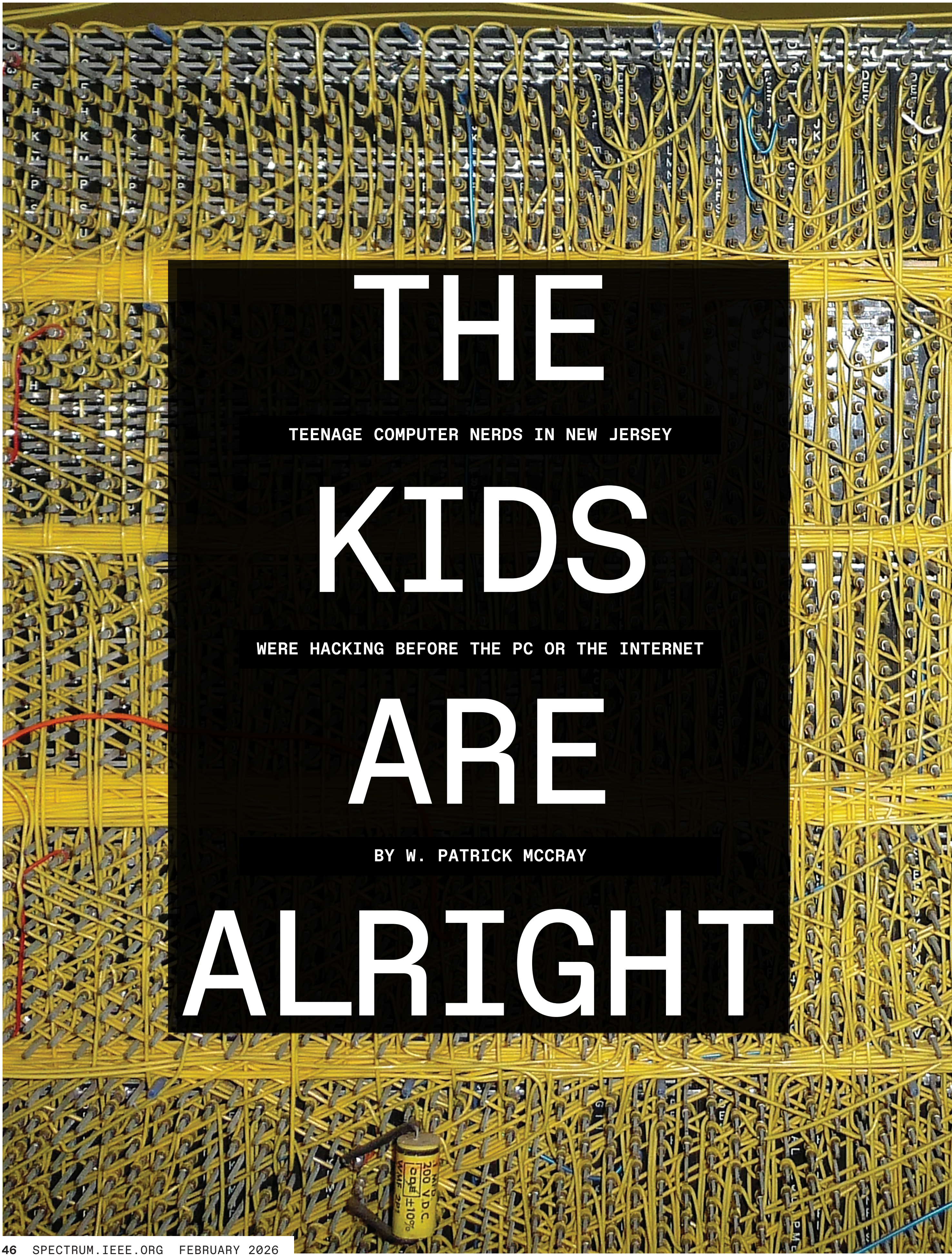
THE MOON is too far away for humans back on Earth to control every rover's action in real time. A shared Spatial Web framework lets lunar rovers continuously update their position, capabilities, and needs with each other. This way, one rover can ask another rover for assistance, even if the rovers come from different countries, space agencies, and manufacturers.



HSML
Each rover is described as an HSML data file outlining every measurement, capability, and status.

HSTP
Rover 2 sends Rover 1 (now stuck) a verified message via HSTP: "May I assist?"

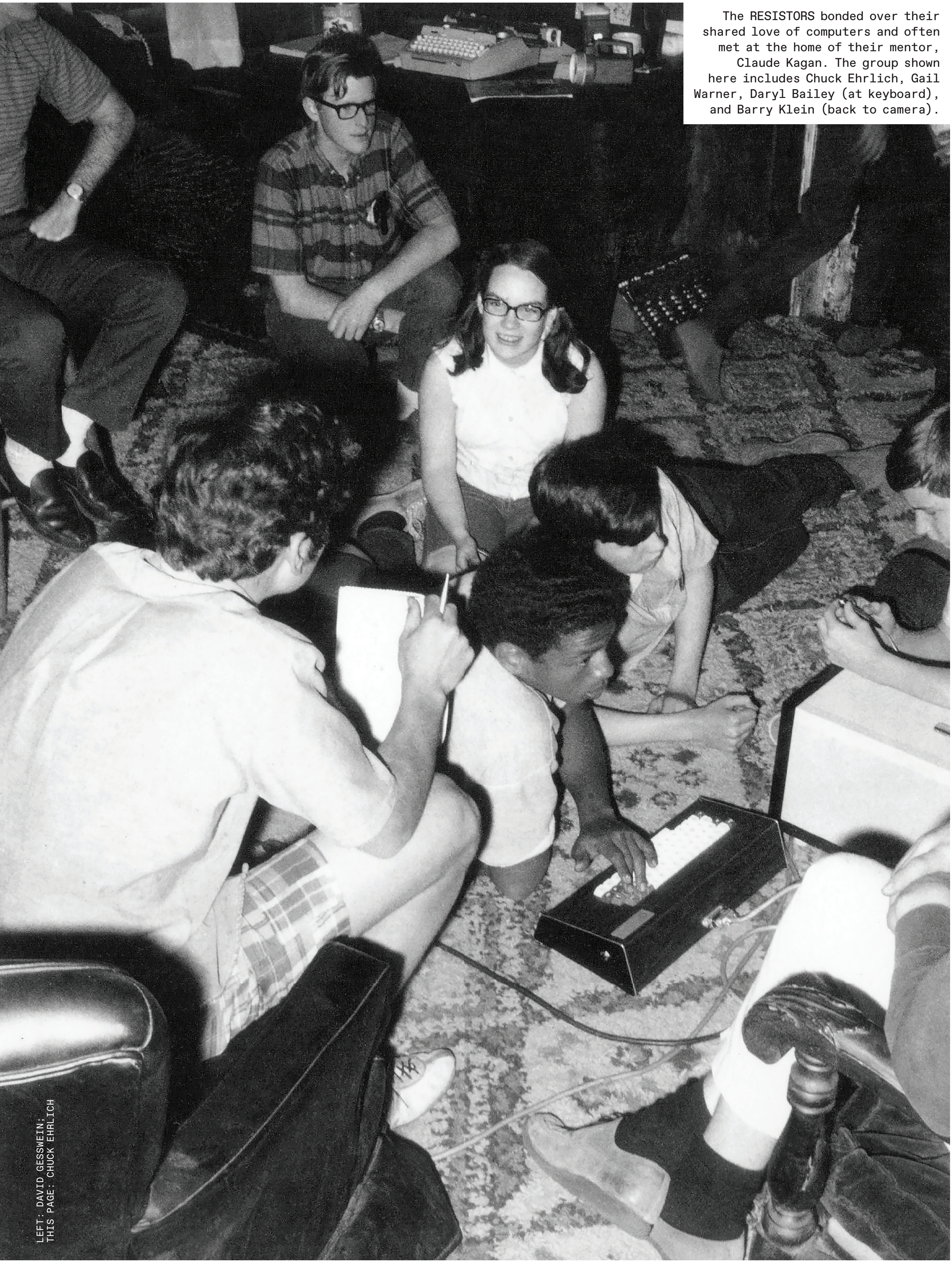
UDG
Via a UDG directory, the astronaut has access to a complete picture of the nearby digital moonscape—all the rovers' locations, abilities, and current activities.



THE KIDS ARE ALRIGHT

TEENAGE COMPUTER NERDS IN NEW JERSEY WERE HACKING BEFORE THE PC OR THE INTERNET

BY W. PATRICK MCCRAY



The RESISTORS bonded over their shared love of computers and often met at the home of their mentor, Claude Kagan. The group shown here includes Chuck Ehrlich, Gail Warner, Daryl Bailey (at keyboard), and Barry Klein (back to camera).

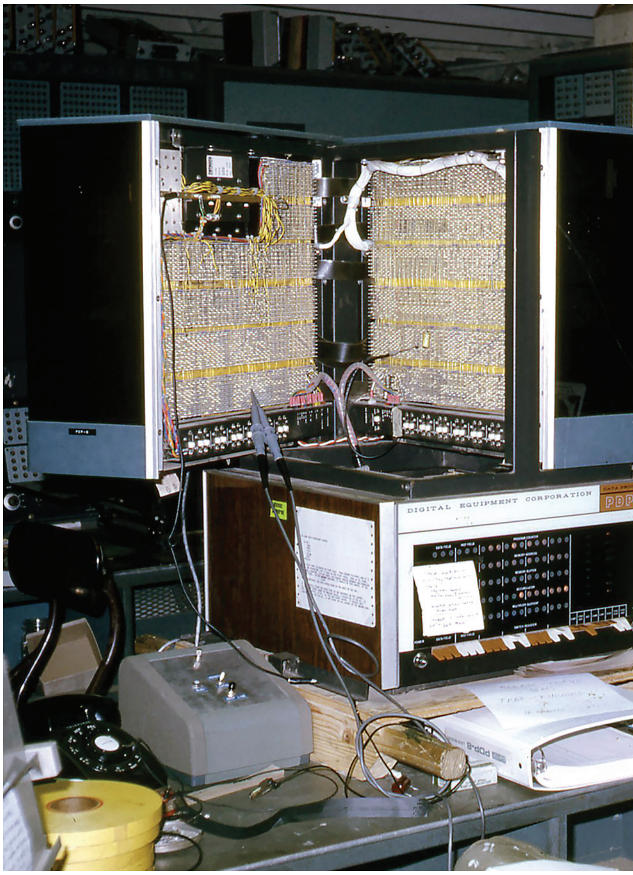
LEFT: DAVID GESSWEIN; THIS PAGE: CHUCK EHRLICH

IN LATE APRIL OF 1968, a computer conference in Atlantic City, N.J., got off to a rocky start. A strike by telephone operators prevented exhibitors from linking their terminals to off-site computers, as union-sympathetic workers refused to wire up the necessary connections. Companies' displays were effectively dead.

But a small cohort of teenage computer enthusiasts from the Princeton, N.J., area flaunted a clever work-around: They borrowed an acoustic coupler—a forerunner of the computer modem—and connected it to a nearby pay phone. With this hardware in place, the youngsters dialed in to an off-site minicomputer.

The teenagers called themselves the RESISTORS, a retronym (they picked the moniker first and then matched words to the letters) for "Radically Emphatic Students Interested in Science, Technology, Or Research Studies." The trade publication *Computerworld* gave the RESISTORS front-page billing—"Students Steal Show as Conference Opens"—and noted how the group drew a "fascinated crowd" of computer professionals. A reporter even suggested that the RESISTORS represented the vanguard of a small-scale social movement as the teens sought to engage with their counterparts from "underprivileged areas of Trenton" and introduce them to personal computing.

In the modern history of computing, a story about a group of teens "playing" with computers might seem tangential. But the previously untold history of the RESISTORS highlights the fact that, years before there were machines called personal computers, some people regularly accessed computers for activities unrelated to their professional lives. Motives varied, but entertainment as well as the display of technical prowess mattered. Just as important, the story of the RESISTORS expands our sense of the hobbyist community beyond later and better-known groups like the Bay Area's Homebrew Computer Club.

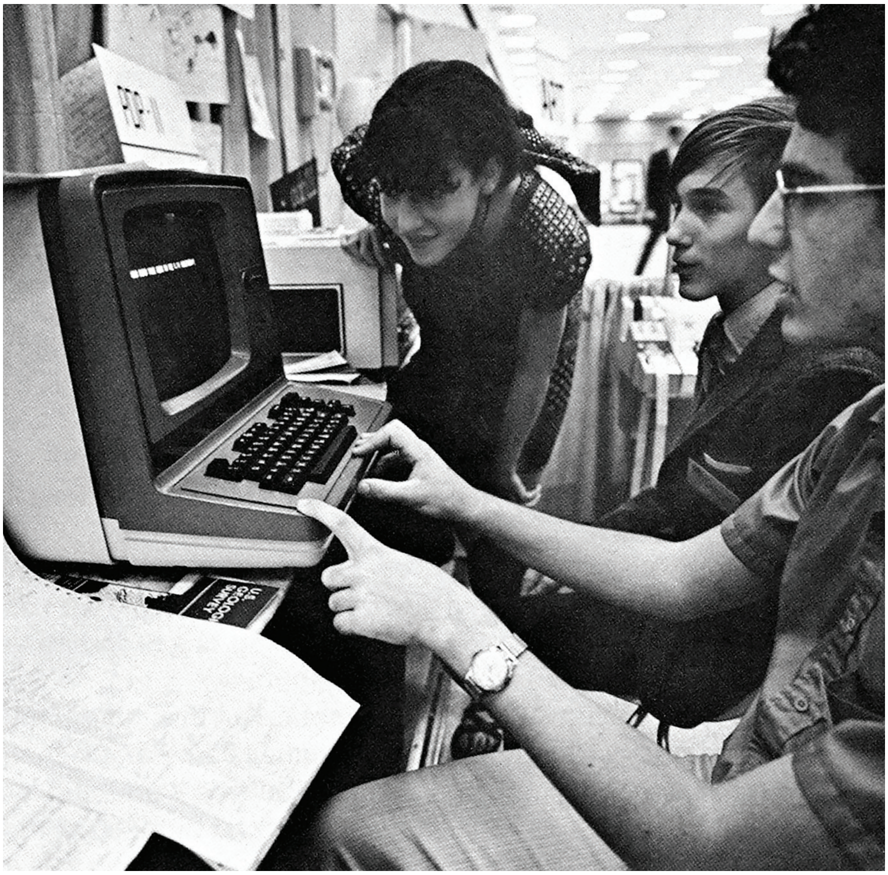


Fewer than 70 kids claimed membership in the RESISTORS over the group's roughly decade-long existence. Nonetheless, a surprisingly large number of them went on to have careers in technology and science. Two members wrote books about computing that would sell millions of copies. Another member cofounded Cisco Systems, which got its start manufacturing Internet routers and other networking hardware and is now a multibillion-dollar business. Others became college professors or professional programmers. And starting around 1969, the RESISTORS became linked to computer pioneer Ted Nelson (more on that later).

An engineer named Claude Kagan was the nucleus around which the RESISTORS first organized. Born in 1924 in Orval, France, Kagan moved to the United States as a teen, served in the army, and earned an M.S. from Cornell University in 1950. He took a position with Western Electric, the manufacturing arm of AT&T, and in 1958, he moved to Hopewell Township, N.J., a short drive from Princeton.

Kagan's specialty was high-level computer languages, such as Fortran and BASIC, in which programmers write code that is largely independent of the particular type of computer. He was also an inveterate collector of old computers and other electronics, which he stored in a large red barn on his property that was also home to some donkeys and malamutes.

Chuck Ehrlich, one of the original RESISTORS and later an entrepreneur and venture capitalist, recalls that in late 1966, he and a small group of



RESISTOR Peter Eichenberger [above left] works on a DEC PDP-8 computer, which Claude Kagan convinced the company to donate to the group.

When the Jewish Museum launched an ambitious art and tech exhibition in 1970, members of the RESISTORS [above right] collaborated with artists and provided tech support.

LEFT: CHUCK EHRLICH; RIGHT: THE JEWISH MUSEUM

"brainy social outcasts" were looking for some sort of clubhouse. The kids weren't interested in smoking pot or social protests, and they were disenchanted with the science classes offered at their local schools. But they were into electronics.

Kagan knew one of the teens' fathers and offered to let the group use his barn. They soon discovered Kagan's collection of artifacts, including a surplus IBM paper-tape punch, some analog telephone equipment, and a Friden Flexowriter (a kind of heavy-duty typewriter that could be linked to a computer).

But the main attraction for the teens were Kagan's computers. The most imposing of these was a Burroughs Datatron 205, a computer first manufactured in the mid-1950s and based on vacuum tubes. The enormous machine weighed several tons, and stories circulated about how Kagan had borrowed a tractor trailer to heroically transport the behemoth from Michigan to New Jersey.

Only slightly less imposing was an inoperable Packard Bell PB250, a refrigerator-size computer of more recent vintage that the teens managed to get working. Kagan also allowed the teens to connect to his employer's DEC PDP-8 machine via teletype over phone lines so they could run programs written in TRAC (Text Reckoning And Compiling). Developed starting in 1959 by computer scientist Calvin Mooers, TRAC was an efficient language amenable to being run on machines that had relatively little memory. The teens were fond of connecting to the off-site computer and accessing a version of Joseph Weizenbaum's ELIZA chatbot program.

Being able to work with computers interactively and in real time was generally unavailable to nonprofessional computer users at the time. Kagan eventually persuaded the Digital Equipment Corp. to donate a PDP-8—no trivial gift, as new models sold for US $15,000 or more—which the RESISTORS worked with in the barn.

The bargain Kagan struck with the RESISTORS was unusual for several reasons. First, Kagan was gay, a fact that the teens (and their parents) were aware of but which, by all accounts, bothered no one. When the Hopewell Valley Jaycee-ettes held a house tour in April 1966, the brochure encouraged people to visit Kagan's "unique bachelor setting" that he shared with artist George Furnish. Furnish passed away around the time the RESISTORS were forming, and the grieving Kagan assumed multiple roles for the group: guru, mentor, publicity agent, and landlord. Kagan provided the space, while the teens were responsible for maintaining both it and the equipment as well as covering the cost of electricity.

Most amateur computer clubs of the era were masculine spaces, but photographs of the RESISTORS almost always show one or more young women working at a terminal or solving a programming problem. When it came to deciding whose turn it was to use a machine, Jean Hunter—later a professor of biological and environmental engineering at Cornell—likened it to social time-sharing that required "beating people over the head to make them give you a turn." John R.

1

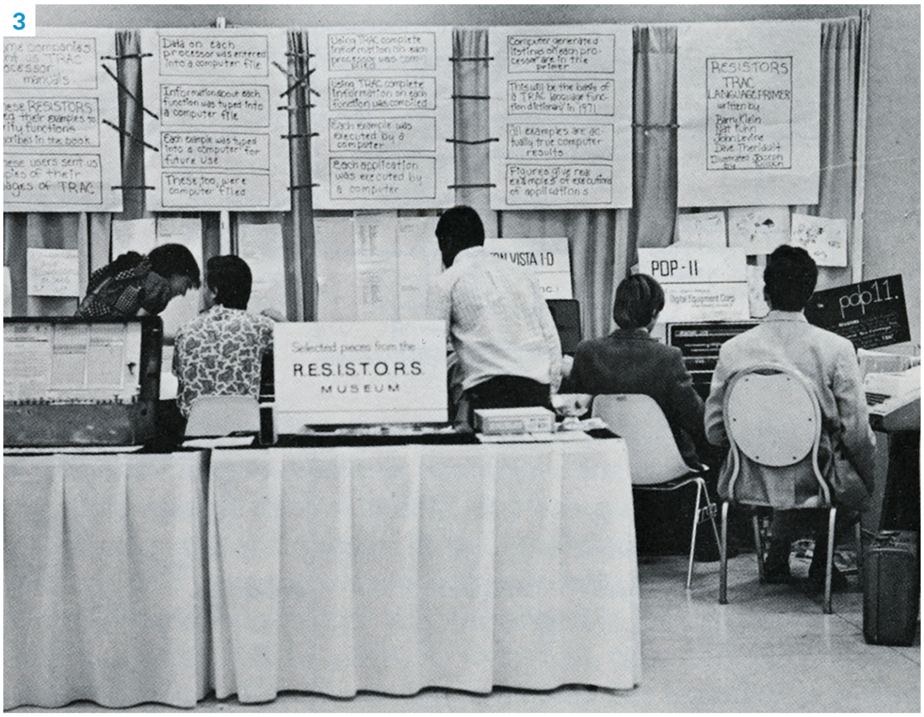
CHA-CHA-CHA !!
OM

2

1: Twelve-year-old Nat Kuhn was just 10 when he joined the RESISTORS. “I was super geeky,” he later recalled. 2: Conceptual artist Agnes Denes [right] programmed her piece *Trigonal Ballet* for the Jewish Museum’s *Software* exhibition with help from RESISTORS [from left] Peter Eichenberger, J Laurence Sarno, and John Levine, as well as Nat Kuhn. 3: The RESISTORS booth at the exhibition featured computer programs written in TRAC. 4: Computer pioneer Ted Nelson met the RESISTORS in the late 1960s, when he was developing his ideas around hypertext and globally interconnected networks for publishing. 5: Electrical engineer Claude Kagan [second from left] encouraged the RESISTORS to learn computing by rehabilitating and writing code for the old computer equipment stored in his barn. 6 & 7: One of the old computers that the RESISTORS encountered in Kagan’s barn was a 1950s-era Burroughs Datatron 205 mainframe. Kagan had reportedly borrowed a tractor trailer to transport the machine from Michigan to New Jersey.

1: DAVID FOX; 2 & 3: THE JEWISH MUSEUM; 4: TED NELSON; 5: CHUCK EHRLICH; 6 & 7: DAVID GESSWEIN

3


Data on each processor was entered into a computer file
Information about each function was typed into a computer file
Each example was typed into a computer for future use
These, too, were computer filed
Using TRAC complete information on each processor was compiled
Using TRAC complete information on each function was compiled
Each example was executed by a computer
Each application was executed by a computer
Computer generated listings of each processor are in the primer
This will be the basis of a TRAC language function dictionary in 1971
All examples are actually true computer results
Figures give real examples of executing of applications
RESISTORS TRAC LANGUAGE PRIMER written by Barry Klein Nat Kuhn John Levine Dave Theriault
VISTA I-D
PDP-11
Digital Equipment Corp
pdp11.
Selected pieces from the RESISTORS MUSEUM

4

5

6

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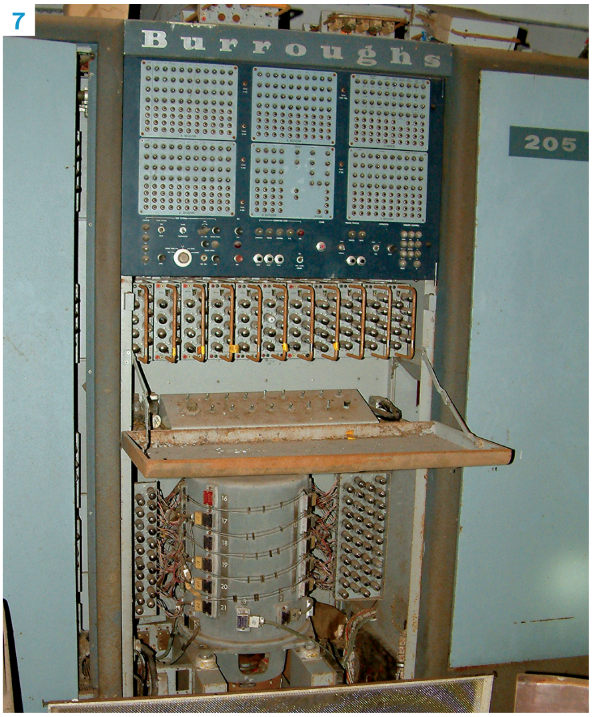


7

Levine, who was a RESISTOR before studying computer science at Yale and later coauthoring the bestseller *The Internet for Dummies*, recalled, "We were so nerdy that it didn't occur to us that girls [would] be any different in terms of what they could do."

There were also efforts to recruit African American teens from schools in Trenton. One of these kids, Joseph Tulloch, provided quirky, Dr. Seuss–like illustrations for a programming manual that Kagan and the teens assembled and published. Tulloch later became a programmer for the state of New Jersey.

New members were initiated into the group by having an omega sign, the engineer's symbol for electrical resistance, drawn on their face with a Magic Marker (these were teenagers after all). One of the first things a new member would learn was how to use TRAC to write programs. For his part, Kagan held a dim view of traditional learning as practiced in local classrooms. He instead insisted that the RESISTORS learn by doing. The group's pedagogical approach came from the African American motto "Each one, teach one." As one member recalled, "if you want to teach someone how to do something, you had to let them sit at the keyboard."

The RESISTORS' location in the Princeton area contributed to their success. Several members had parents employed at nearby technology companies, such as AT&T and RCA. Others, such as Nat Kuhn, had parents who worked at Princeton University. Kuhn's father was Thomas Kuhn, a historian and author of *The Structure of Scientific Revolutions* (1962), the landmark book that introduced "paradigm shift" into the vernacular.

As a kid, Nat built devices from hobbyist electronics kits with his father, a former physicist. Nat joined the RESISTORS after attending an open house the group sponsored in February 1968 at the Princeton Junior Museum. He was just 10 years old at the time. "I was super geeky," he recalled, "and the computer became my hobby and obsession. You could understand things through it and make things happen."

Soon after Nat had his face inked with an omega sign, another person, much older but just as passionate about personal computing, started showing up at Claude Kagan's barn.

Ted Nelson had majored in philosophy at Swarthmore College, graduating in 1959, and then studied sociology at the University of Chicago and later Harvard, where he took his first computer course. Nelson's 2010 autobiography includes a whole chapter, titled "The Epiphany of Ted Nelson," about this revelatory experience. When he realized that the computer, instead of a dreary number-crunching device, "could be whatever it was programmed to be," his "world exploded."

Nelson had a penchant for writing, and so an even bigger revelation was that computers could handle text by manipulating, storing, printing, and, above all, displaying it on screens. And, if this could be done with text, it could probably also be done with images and sound. "The future of mankind was at the computer screen," he decided, as the "interactive computer would become the workplace of the future."

Equally profound for Nelson was recognizing that once a person had text on a computer screen, they could use it to construct parallel, nonsequential textual passages. These word assemblages could then be linked to one another or branch off in entirely new directions—a farsighted idea for the time.

In 1964, Nelson accepted a teaching position at Vassar College, where his new colleagues invited him to describe how the future of work and artistic creativity would happen on computer screens. In the promotional flyer for the talk, he introduced a new word: hypertext.

As Nelson defined it in a 1965 paper, hypertext meant "a body of written or pictorial material interconnected in such a complex way that it could not conveniently be presented or represented on paper." Almost any topic could, in principle, be represented on a computer screen with "links" connecting one entry to another, along with annotation, footnotes, and summaries, while also including "every feature a novelist or absent-minded professor could want."

Nelson imagined that his system of information storage, retrieval, and documentation could "grow indefinitely," containing more and more of the world's knowledge while revealing important connections between all of the entries.

Nelson soon quit Vassar and started raising money and his professional profile. His goal was to design and implement a universal text handling, publishing, and globally connected electronic library system, which he named Project Xanadu, from Samuel Taylor Coleridge's "Kubla Khan." (It's also the name of Charles Foster Kane's mansion in Orson Welles's 1941 classic, *Citizen Kane*.) Xanadu would turn into Nelson's lifelong obsession.

The catalyst that brought Nelson together with Claude Kagan and the RESISTORS wasn't some new computer but an avant-garde art show. In the fall of 1970, a lavish exhibition titled *Software* opened at the Jewish Museum in New York City. Museum director Karl Katz handpicked the influential art theorist Jack Burnham to curate the show. Burnham, in turn, was inspired by Norbert Wiener's cybernetic concepts and wanted to explore how conceptual artists might experiment with new computing technologies, such as "real-time computing" and "interactivity," in a gallery setting. The exhibition gave thousands of visitors an opportunity to see, and in some cases use, minicomputers, teletype equipment, high-speed copy machines, and closed-circuit television.

A contributor to the show and its technical adviser, Ted Nelson recruited the RESISTORS to help him and some of the artists. As he later wrote in his influential 1974 book *Computer Lib/Dream Machines*, "Some people are too proud to ask children for information. This is dumb. Information is where you find it." For Agnes Denes, a Hungarian-born conceptual artist, the teens coded a minicomputer to animate triangles on a screen for a piece called *Trigonal Ballet*. For conceptual artist Carl Fernbach-Flarsheim, the teens used the I Ching to program a piece called *Conceptual Typewriter*. A visitor could select one of several buttons, such as "the silent" (represented by a circle) or "the providing" (illustrated by sheaves of wheat), and then use a light pen to alter the image. Both artists provided the initial ideas, but the RESISTORS executed them.

Nelson, working with programmer Ned Woodman, contributed a piece titled *Labyrinth*. Running on a PDP-8 that DEC provided, *Labyrinth* was explained as "the first public demonstration of a hypertext system." To use it, a visitor would sit at a terminal and begin reading the displayed text. For the passage "The exhibition you are attending is called Software. It was organized by Jack Burnham," you could use keystrokes (such as *F* for "forward") to navigate the text and retrieve a definition of "software" or biographical details about Burnham.

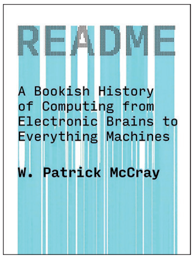
For many museumgoers, the entire exhibition suggested a technological future where people easily navigated the information-rich realm of what would become known as cyberspace.

The RESISTORS, meanwhile, gradually faded throughout the 1970s as its members went off to college and the supply of new recruits dwindled. Nonetheless, members like Nat Kuhn and John Levine recall that ideas they bantered about in bull sessions with Nelson in Kagan's barn materialized later in the pages of *Computer Lib/Dream Machines*. "There was certainly very little in that book that we hadn't already heard about before it appeared," Levine said.

When I talked with former RESISTORS, it was surprising to hear how many members remained in touch with one another more than a half-century later. Many of them still included their participation on résumés. Courtships formed, and at least two members married each other. Their activities left a long-lasting echo in the world of computing as well. Len Bosack cofounded Cisco Systems. Cynthia Dwork, a professor of computer science at Harvard, made pioneering contributions to cryptography. Steve Kirsch was one of two people to invent the optical mouse and went on to become a successful tech entrepreneur.

Even as the RESISTORS were fading as a group, massive technological changes were just over the horizon. Personal computers, introduced in the early 1970s, soon became consumer goods found in hundreds of thousands of homes. That technological revolution would be solidified when *Time* named the PC "Machine of the Year" in 1982. New computing worlds beckoned to experts and neophytes alike, but it was a future that a group of teens in a New Jersey barn had already seen and lived. ■

This article is adapted from the author's new book, *README: A Bookish History of Computing from Electronic Brains to Everything Machines* (The MIT Press, 2025).



README

A Bookish History of Computing from Electronic Brains to Everything Machines

W. Patrick McCray

MIT PRESS

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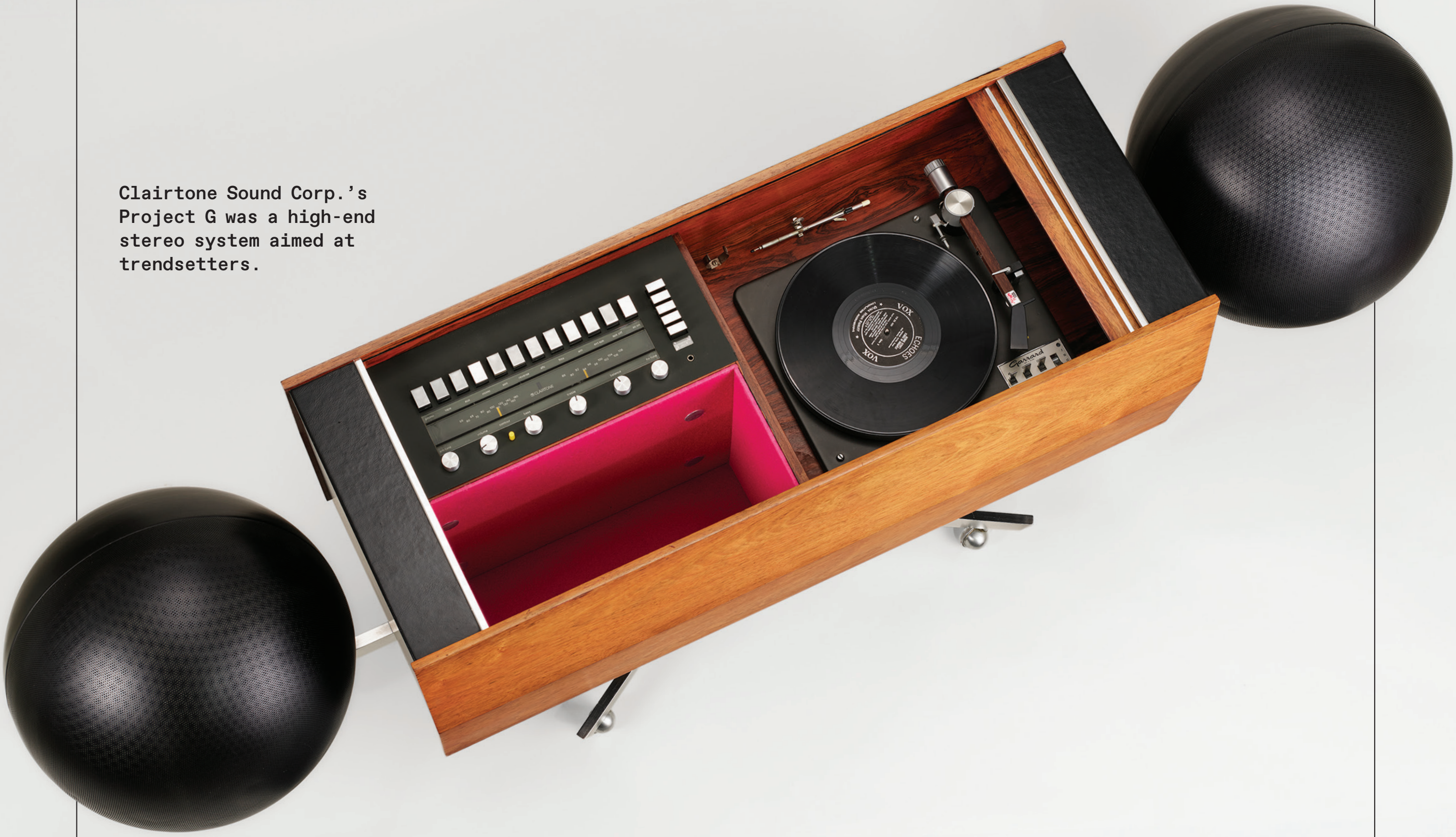
BY ALLISON MARSH

Past Forward



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The Project G Stereo Defined 1960s Cool

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FOR MORE ON CLAIRTONE AND THE PROJECT G, see spectrum.ieee.org/pastforward-feb2026

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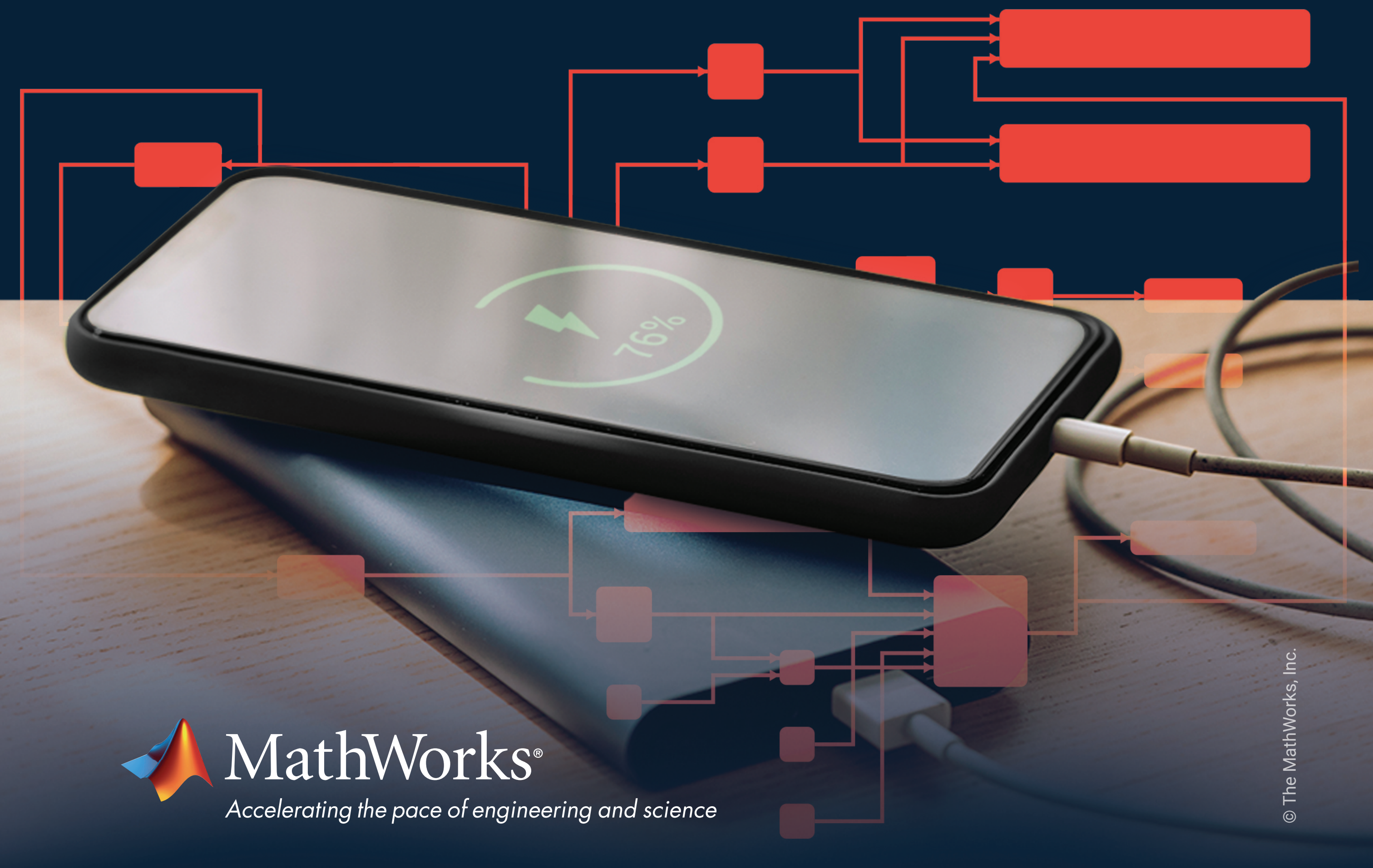

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